"Fear not as much a cloud from the land as from the ocean in winter;

Photographs by John Dungan, Lieutenant (j.g.), U.S.N.

But in the summer a cloud from a darkling coast is a warning."

—Theophrastus of Eresus

An Illustrated Outline of
WEATHER SCIENCE

by

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CHAPTER I

OUTLINE OF METEOROLOGICAL HISTORY

I. EARLY TRENDS

The development of meteorology and weather lore has always been dependent on the weather in its relation to the security and comfort of a people. In those civilizations where the weather was seldom rigorous little was done toward the development of either a system of meteorological lore or a science of the weather. On the other hand, those civilizations dependent on the weather for their continued security and prosperity developed elaborate weather superstitions and, in some cases, the beginnings of a weather science. These early trends toward scientific meteorology were usually observational and deductive with little tendency toward an inductive development and the use of instruments for observational purposes. The invention of instruments and the development of physical theories came about at a later date. The early approaches to science in weather study utilized mainly a systematic accumulation of observational data and systems of classification and organization of these data. The method was largely cumulative rather than experimentally scientific.

II. THE EGYPTIANS AND BABYLONIANS

A. While the Egyptians developed such sciences as astronomy and related sciences they did little to develop a science of the weather. Their independence of the weather due to the presence of the Nile for irrigation purposes discouraged the development of meteorology in ancient Egypt.

B. The Babylonians enjoyed a mild climate although not quite so equable as that of the Egyptians. At a very early date they developed a wind rose of eight rhumbs. During the interval from about 700 to 900 B.C. the Babylonian knowledge of atmospheric phenomena was formed into the semblance of a profession by the priests and correlated with their astronomical knowledge to form a system of astro-meteorology.

III. GREEK WEATHER LORE (400-300 B.C.)

A. Aristotle collected all the previous writings on meteorology in his treatise, *Meteorologica*. For nearly 2000 years the *Meteorologica* remained the standard textbook on weather. The four

books comprising the *Meteorologica* contained a much wider range of subjects than is now believed to be the scope of the science. Everything of a physical nature pertaining to the earth, sea or air was included. Quotations and criticisms of Pythagoras, Anaxagoras, Socrates, Hippocrates and Democritus, his predecessors, and their concepts of the subject were included.

B. Theophrastus (about 375-285 B.C.) was a pupil of Aristotle. His treatise on the weather represented a combination of science and folklore. Theophrastus' *Book of Signs* contained at least 80 signs for rain, 45 signs of wind force and direction, 50 for storms and 20 for fair weather.

1. The main essence of some of his quotations having a more scientific aspect is given below.
   a. Little rain will occur when there is fog.
   b. When winds conflict with one another hurricanes and cloudbursts may occur.
   c. Rain may be expected when the clouds are like huge fleeces of wool.
   d. Streaks of clouds from the southward indicate rain within three days.
2. On the other hand, many of the signs given by Theophrastus represented merely a compilation of the folklore on the subject. Representative extracts are given below.
   a. Sheep and cattle fighting more than usual for their food, or an ass shaking its ears excessively, indicates a storm.
   b. When flies bite vigorously it is a sign of rain.
   c. If cattle eat more than usual and lie down on the right side rain is to be expected.
   d. If many berries are found on the scarlet oak many storms will occur.
   e. If nonaquatic birds wash themselves, it indicates either rain or storms.

IV. ROMAN WEATHER LORE

Little was added to the science of meteorology by the Romans. Even the folklore on the subject was borrowed from Theophrastus.

The most notable Latin treatise was written by Virgil. Representative extracts from Virgil's first book of the *Georgics* are included below.

a. The crane soaring high, the heifer gazing up into the sky and snuffing the breeze, the swallow darting in circles around the pond and the croaking of frogs all portend rain.

b. A rising sun when dappled and sunk in a mist indicates showers. This sign further indicates that a gale is bearing from the seaward.
c. Falling stars with long tails indicate a gale.
d. When light chaff and leaves flutter in the air as they fall, or feathers dance along the waves, a storm and gale will occur.

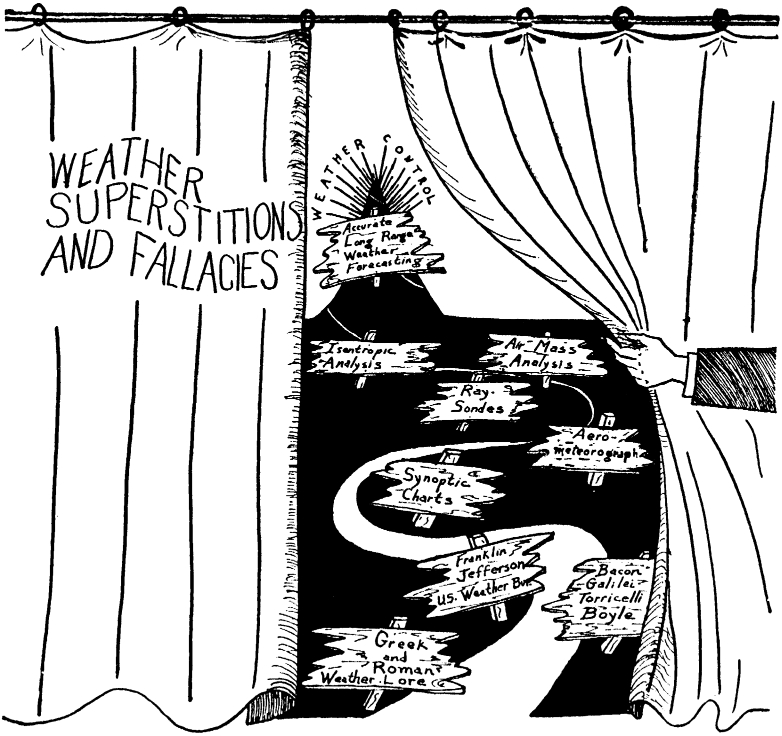


Fig. 1

V. THE MEDIEVAL PERIOD

A. An example of the tendency to maintain the authenticity of the old proverbs and superstitions about the weather is exemplified by some of the following quotations and extracts.

1. Erasmus Darwin wrote a summary of this common weather lore in verse form. Following is a selection:

a. The hollow winds begin to blow,
The clouds look black, *the glass is low,*
The soot falls down, the spaniels sleep,
The spiders from their cobwebs peep.

Last night the sun went pale to bed,
The moon in halos hid her head,
The boding shepherd heaves a sigh,
For, see! a rainbow spans the sky.

b. The only sign of advancement from the time of Theophrastus is the mention made of a meteorological instrument.

2. *The Shepherd of Banbury's Rules* are of obscure origin. They were first published in 1744 by a Mr. Claridge but their authorship is believed to be much earlier. They are interesting because they represent a rather unique collection of astro-meteorology, cumulative methods and folklore. The following extracts were made from these rules.

a. When the time is near to the full moon and the sun rises into a mist there will be fair weather.

b. When there are mists in the time of the old moon there will be rain in the time of the new moon.

c. If rain is sudden it will not last long.

d. When the air becomes thicker by gradual degrees and the moon and stars or the sun shine continually dimmer, *then it is likely to rain in six hours usually.*

e. When the sun rises fiery and red, wind and rain will follow.

f. When it is cloudy and the clouds decrease fair weather may be expected.

g. When mists appear over the low ground and soon vanish, fair weather may be expected.

h. When mists continue to rise to the level of the hill-tops rain may be expected within a day or two.

i. During the summer or fall when high towering clouds with black on the nether side are observed after the wind has been from the south for two or three days, thunder and rain will occur suddenly.

j. It is time to make haste to shelter when two such clouds arise, one on either hand.

k. When a cloud is seen arising against the wind or side wind the wind will blow the same way that the cloud came when it gets up to your place of observation.

l. Fair weather may be expected for several days when the clouds are small, round and dapple gray and fly with a north wind.

m. When small clouds increase there will be heavy and continued rain.

n. Fair weather will follow the decrease of large clouds.

o. South winds and fair weather for a week are likely to produce a great drought.

p. The strongest winds occur when the wind shifts from the south to the northwest.

q. If it starts to rain before sunrise it will cease before noon.

r. If the rain starts within two hours after sunrise the rain will continue through the day unless the rain was preceded by a rainbow.

s. When there is much snow and frost in October and November, January and February will be mild.

t. If the last eighteen days of February and the first ten days of March are rainy, then the spring and summer quarters are apt to be rainy also.

B. Astro-meteorology. Since the beginning of weather science many people have fancied a relationship between the movement of celestial bodies and weather changes. Study of the movements of the sun, moon, stars and planets gave rise to astrological forecasts. With the invention of printing, these astrological forecasts received wide distribution and did much to influence popular beliefs. These mystical astrological forecasts, of course, receive no credence in modern science. However, another type of semi astro-meteorology has some scientific basis. Those weather proverbs and folk sayings which tell of the appearance of celestial objects as influenced by the conditions of the intervening atmosphere often represented visual recognition of physical processes. Recently a special study has been started of a celestial object, the sun, in order to understand better the sunspots which have been found to influence the weather indirectly.

1. Astrology and astrological terms, as applied to the weather, have exerted an influence on our language as exemplified by the words jovial, saturnine, martial, and mercurial. Proverbs based solely on astrology have little scientific meaning. For example:

   a. "The prudent mariner oft marks afar
   The coming of tempests by Böotes's star."

   b. "The bonnie moon is on her back;
   Mend your shoes and sort your thack."

   c. "It is sure to be a dry moon if it lies on its back so that you can hang your hat on its horns."

2. The weather sayings concerned with both celestial objects and atmospheric phenomena are represented as follows:

   a. "When the stars begin to huddle,
   The earth will soon become a puddle."

b. "When the stars begin to hide,
Soon the rain will betide."

c. "Moonlight nights have the heaviest frosts."

d. "Clean moon,
Frost soon."

e. "When the sun is in his house it will rain soon."

VI. THE DEVELOPMENT AND USE OF INSTRUMENTS

A. After the early beginnings which were limited to visual observational methods, the era of instruments opened new vistas of advancement to the weather science. The nearly infinite difficulties encountered by these early experimenters with new methods and procedures are usually not recognized by the modern student in this scientific age. To illustrate these difficulties, and the matter of their solution, the following brief history of the development of thermometry is offered.

B. Early Thermometry. The prototype of the modern thermometer, consisting of a expansible liquid in a sealed tube, was developed in Italy. The first sealed-stem thermometer was made at the Florentine Academy in 1682. One of the most difficult concepts for these early experimenters to master was that of reliable reference points. Many repeated experiments were made to obtain high points and low points on the sealed-tube thermometer and establish divisions in between. In 1688 Dalence used the temperature of air during freezing for his low point and the temperature of melting butter for the high point. Other experimenters used the heat of summer and the cold of winter or ice at the severest frost. Even the temperatures of deer and cows' blood were used at various times. Of course, the obvious fault with these reference points lies in the fact that they vary from one time to the next and have no constant value.

1. About 1710 Gabriel Daniel Fahrenheit invented the thermometer scale which bears his name. The zero point on this scale was determined by the temperature of a certain cold winter's day in Danzig. This point was later specified as the temperature of a given mixture of ammonium chloride, common salt and snow. The other reference point was taken as what he erroneously believed to represent the normal temperature of the human body. The interval between these two reference points was ultimately divided into 96 divisions or degrees. On this illogical scale the freezing point of water fell at 32° and at sea level the boiling point fell at 212°. This scale has the advantage of natural small scale divisions and the further advantage that, in temperate or

torrid zones, it is rarely cold enough to require negative readings.

2. In 1731 the French philosopher and scientist Réaumur invented a temperature scale. This thermometer made use of alcohol as the expanding liquid. The zero reference was the freezing point of water. A degree was arbitrarily taken as one thousandth of the volume contained by the bulb and tube up to the zero mark. The boiling point of water at standard conditions falls at 80° in this scale.
3. The Centigrade scale was designed by the Swedish astronomer, Anders Celsius, about 1742. Originally the scale was graduated downward from the boiling point of water, at standard conditions, which was taken as 0°, to the freezing point of water at 100°. The degree is thus defined as one hundredth of the difference between the two reference points. The modern Centigrade thermometers have reversed the original scale so that now freezing occurs at 0° and boiling at 100°.
4. The Absolute or Kelvin scale of temperature was developed by Lord Kelvin after 1850. This scale starts at the Absolute zero (— 273.13° C. or — 459.6° F.). For most work the Absolute scale assumes an Absolute zero of — 273°, thus the freezing point of water on the Absolute scale becomes 273° A. and the boiling point 373° A.

VII. THE DEVELOPMENT OF METEOROLOGY AS A SCIENCE

A. Francis Bacon (1561-1626), author of *Novum Organum*, and an exponent of the inductive method, is believed to have made some contributions to the adoption of the scientific method in meteorological circles.

B. Galileo Galilei (1564-1642) was the inventor of an air thermometer in addition to his triumphs in many other fields of science. He is also believed to have first given Torricelli a clew as to the true nature of atmospheric pressure.

C. Evangelista Torricelli (1608-1647) discovered the principle of the barometer.

D. Robert Boyle (1627-1691) experimented with the physics of gases. He discovered and gave name to the law expressing the relation of volume to pressure. The expression of this law was the first step toward a dynamics of the atmosphere.

E. Robert Hooke (1635-1703) received his first opportunity as an assistant to Robert Boyle. They were both members of the "Invisible College" which later became the Royal Society. In addition to his many contributions to general physics, Hooke

invented several meteorological instruments including a wind gauge, wheel, double and marine barometers and a rain gauge (Fig. 2).

F. Edmund Halley (1656-1742) has been called by many the "father of dynamical meteorology" because he endeavored to connect the distribution of the sun's heat over the earth's surface with the general circulation of the atmosphere.

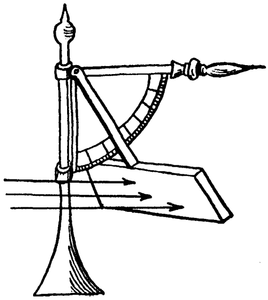
G. Benjamin Franklin (1706-1790) was awarded the Copley medal of the Royal Society for his famous experiment with kites in his study of atmospheric electricity in 1752 which led to his invention of the lightning rod. He is believed to be the first American to recognize the general west-to-east movement of the weather in temperate regions of North America.

H. During the period from 1600 to 1850 there were many developments in meteorological instruments. Some of these have already been mentioned in more detail. However, the main improvements of note were as follows:

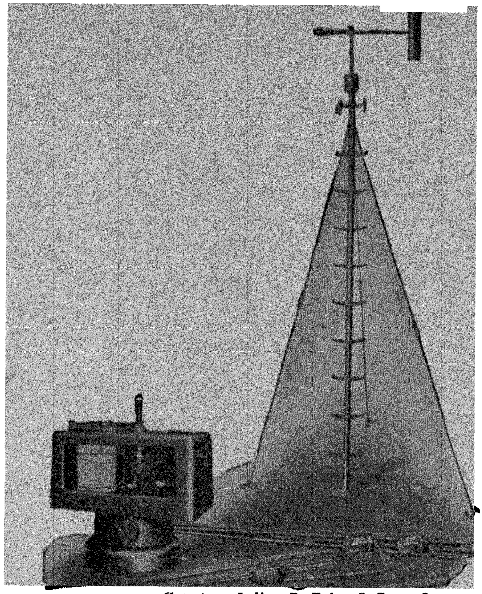
1. The first Florentine thermometers were originated about 1600.
2. Ferdinand II, of Tuscany, invented the condensation hygrometer in 1650.
3. Wren's meteorograph was first demonstrated in 1664.
4. From the period 1665 to 1736 the various thermometer scales were originated.
5. Around 1750 Benjamin Franklin experimented with atmospheric electricity and about that time he invented the lightning rod.
6. In 1783 de Saussure invented the hair hygrometer.
7. The anemometer is credited to Waltman in 1790.
8. Assmann invented the psychrometer in 1825. This was followed by the inventions of the pyrheliometer by Pouillet in 1837 and the aneroid barometer by Vidie in 1847.

I. In addition to these instrument inventions many milestones were being passed in the development of the theoretical aspects of the science.

1. In 1624 von Verulam first indicated the significance of the rotation of the winds with the sun.
2. In 1687 typhoons were recognized by Dampier as revolving storms.
3. Dalton made early discoveries about the gas laws in 1793.
4. In 1805 Beaufort originated the Beaufort scale of wind force.
5. Carots made many studies about heat and radiation about 1820.

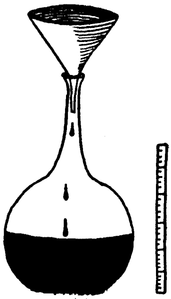


Hooke's plate anemometer.

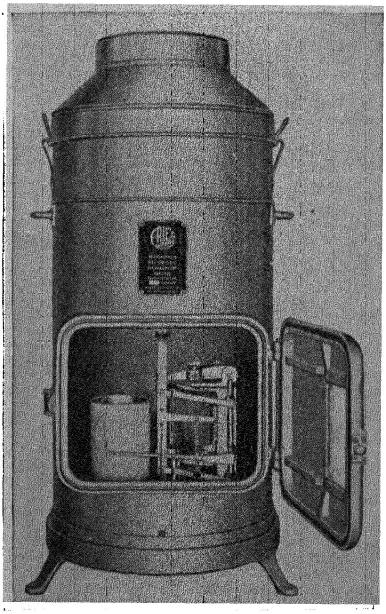


Courtesy Julien P. Friez & Sons, Inc.

Anemograph—mechanical wind direction and velocity recorder.

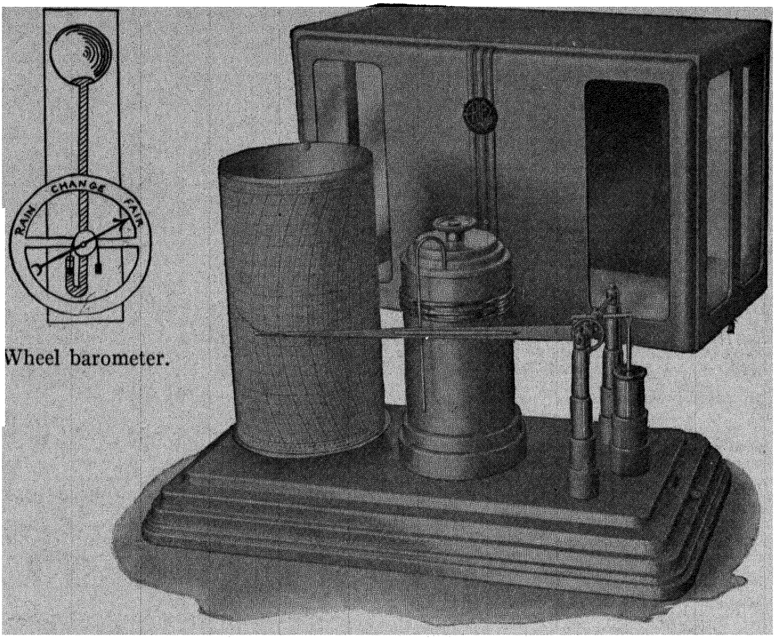


Early rain gauge.



Continuous weighing rain gauge.

Fig. 2



Wheel barometer.

Microbarograph.

Fig. 2—concluded.

6. Pouillet first expounded the idea of the solar constant in 1837.

VIII. THE DEVELOPMENT OF THE SYNOPTIC CHART AND UNIFIED WEATHER NETWORKS

A. The earliest weather charts may be traced back to Brandes in 1820. About 1860 Napoleon III, the French emperor, instructed the scientist Le Verrier to develop a system of weather forecasting. The early work done by Le Verrier gave rise to a wave of enthusiasm. Within a few years networks of meteorological stations developed in many countries. Since the rules of thumb and statistical methods, used for forecasting at that time, were soon proved to be inadequate the early enthusiasm quickly waned. The early progress was then followed by a profound lull.

B. Descriptive and statistical meteorology, on the other hand, continued at a good pace during the period of Le Verrier's frustrations.

   1. The first map of world pressure was produced by Buchan in 1869. Mohn followed this accomplishment with an atlas of storms in 1870.

2. Loomis studied the statistics of precipitation and in 1882 he prepared the first world map of precipitation.
3. Hann prepared the first meteorological atlas in 1887.

C. In the middle of the nineteenth century the invention of the telegraph made possible the collection of a great many simultaneous observations and the construction of a daily weather chart. Networks of stations were organized, government subsidies obtained, and the nucleus of the present elaborate weather systems was first created.
1. The use of the electric telegraph for transmitting weather observations for forecasting purposes was first proposed by Carl Kreil, at Prague, in 1842.
2. In 1848 John Ball made a similar, but more elaborate, proposal to the British Association.
3. In the United States the proposal was first made by Henry, Secretary of the Smithsonian Institution, in 1849.

D. In 1860 the first organization of a service of forecasts and storm warnings in Europe was accomplished by Buys Ballot, Professor of Physics at the University of Utrecht in Holland.

E. The Meteorological Office in London was established in 1854 as a department of the Board of Trade. Admiral Fitzroy was placed in charge. The Meteorological Committee of the Royal Society was organized and started to function in 1867 after considerable preliminary work by Francis Galton. Due to the tendency for scientific circles to expect astronomical accuracy from weather forecasting, the work of the early committee met many reverses in England. In 1872, international co-operation had been obtained by an international meeting of meteorologists. However, it was not until 1879 that a unified weather service was finally able to get under way in England.

F. As previously mentioned, due to the work of Le Verrier, the weather service of France is unbroken from 1863. From that time to the present a daily weather report has been made and issued to the various French ports.

G. In North America the first two weather stations had been established by Thomas Jefferson in 1772. One station was established at Monticello and the other at Williamsburg. However, the United States Weather Bureau, as we know it today, was first provided for by the bill of February 9, 1870. The first bureau was under the direction of the Secretary of War. The following is quoted from the original bills. Points indicative of dominating trends in meteorological interest are italicized.
1. Bill of February 9, 1870 (Under Secretary of War).
Be it resolved by the Senate and House of Representatives of the United States of America in Congress assembled.

That the *Secretary of War* be, and he hereby is, authorized and required to provide for taking meteorological observations at the *military stations* in the interior of the continent and at other points in the States and Territories of the United States, and for giving notice on the northern lakes and on the seacoast, by magnetic telegraph and marine signals, of the approach and force of storms.

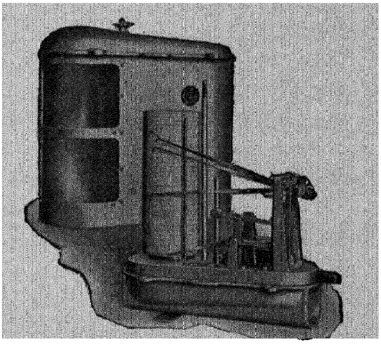
2. Bill of June 10, 1872.
   The appropriation bill approved provided: For expenses of storm signals announcing the probable approach and force of storms throughout the United States, for the benefit of commerce and agriculture; and that the *Secretary of War* be, and hereby is, authorized and required to provide, in the system of observations and reports in charge of the *chief signal officer* for such stations, reports, and signals as may be found necessary for the *benefit* of *agriculture* and *commercial interests.*
3. Bill of October 1, 1890.
   Transfer to Dept. of Agriculture from signal officer. The *Chief of the Weather Bureau,* under the direction of the *Secretary of Agriculture,* shall have charge of forecasting the weather; the issue of storm warnings; the display of weather and flood signals for the benefit of *agriculture, commerce,* and *navigation;* the gauging and reporting of rivers; the maintenance and operation of seacoast telegraph lines and the collection and transmission of marine intelligence for the benefit of *commerce* and *navigation;* the reporting of temperature and rainfall conditions for the *cotton interests;* the display of frost, cold wave, and other signals; the distribution of meteorological information in the *interest* of *agriculture* and *commerce;* and the taking of such meteorological observations as may be necessary to establish and record the climatic conditions of the United States, as are essential for the proper execution of the foregoing duties.
4. With the increasing importance of aviation the United States Weather Bureau found it necessary to expand to meet airway needs in 1926, 1938 and 1940.

IX. THE STUDY OF THE UPPER AIR

The study of the upper air was begun with the first scientific balloon ascents by Charles in 1803.

1. In 1890 mountain observatories were erected to study conditions in the free air.
2. During the period from 1870 to 1910 balloons and kites were used extensively for meteorological purposes.

3. The era of the modern methods in the investigation of the upper air may be dated from Hermite and Besançon experiments starting in 1892.
4. In 1907 Dines developed a meteorograph which did not depend upon the functioning of a clock. This most interesting and original instrument has been modified by several meteorologists such as Patterson of Canada. Regener and Dines devised methods for obtaining samples of air from great heights. Simpson and Scrase have devised an ingenious recording electrometer for measuring the earth's electrical field.
5. In addition to the nonradio type balloon meteorograph, from 1917 the airplane meteorograph has also contributed much to the study of the upper air. One of the best-known types of aerometeorograph is the Lindenberg pattern meteorograph, made by J. and J. Bosch (Fig. 3).



Courtesy Julien P. Friez & Sons, Inc.

Fig. 3. Aerometeorograph.

6. With the development of the vacuum-tube oscillator it became possible to construct instruments to transmit meteorological information about the upper air automatically from a free balloon. Such methods had been suggested by Buys Ballot as early as 1868, and again by Olland in 1875. In 1917 F. Herath and M. Robitsch developed a method for transmitting signals from a meteorograph along the kite wire. This method never gained wide recognition, and it was not until Bureau and Idrac, in 1927, received weather signals from a small radio transmitter attached to a balloon that had reached the stratosphere that the present type radio meteorograph started its development. Since this initial experiment, many such instruments have been constructed, some types of which have proved very successful.

Since the results are immediately available such observations may be used for actual forecasting.

X. *AIR MASS AND FRONTAL ANALYSIS METHODS*

A. About 1840, Redfield recognized the extratropical cyclone as a revolving storm. In the same year Dove published his theory of storms in which he indicated that storms originate when polar and tropical air are brought into juxtaposition. This treatise was probably the earliest forerunner of modern methods. In 1852, Blasius advanced the thesis that advancing cold, polar air underrunning a warm, nearly saturated tropical air would push it upward causing the formation of cumulus clouds and precipitation.

B. In the United States the basic hypothesis of the polar front theory was first advanced by Bigelow in 1900. He maintained that large opposing currents of dissimilar air in the temperate latitudes were basically responsible for weather conditions. Of course, this is the main contention of present-day methods. However, Bigelow's ideas were not developed due to the universal adoption of pressure-type forecasting. The main exponents of this latter type of forecasting procedure were Abercromby and Marriot (Fig. 4).

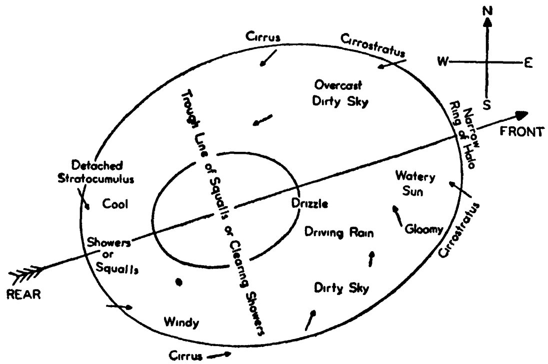


Fig. 4. Abercromby's weather in a depression (Northern Hemisphere).

C. During the period of 1914-18 of World War I, a group of Norwegian scientists began to experiment with Dove, Blasius and Bigelow's ideas. Shaw and Lempfert had furnished them with the observational data for our present concept of the extratropical cyclone. Helmholtz, Margules and V. Bjerknes studied the concept of atmospheric fronts and their effects. J. Bjerknes, the son of V. Bjerknes, and H. Solberg began in 1918 to make

practical application of these methods to forecasting procedures. Since then the forecasting methods of air mass and frontal analysis have been nearly universally adopted.

D. Probably the latest innovation in forecasting procedure, and the method most likely to produce revolutionary advances in the science, is the method known as isentropic analysis which is now being developed by Rossby and his collaborators at the Massachusetts Institute of Technology and the University of Chicago.

TEST QUESTIONS ON METEOROLOGICAL HISTORY

1. Early meteorology was largely a(n) (inductive, deductive) method.
1. ________

2. The study of weather was probably most important to the (Greeks, Babylonians, Egyptians). 2. ________

3. The (Greeks, Babylonians, Egyptians) were most interested in astro-meteorology. 3. ________

4. The *Meteorologica* was written by (Virgil, Aristotle, Theophrastus, Democritus). 4. ________

5. Criticisms of Pythagoras were included in (*The Book of Signs*, First Book of the *Georgics*, *Shepherd of Banbury's Rules*, *Meteorologica*).
5. ________

6. The material in Virgil's book on the weather was borrowed largely from (Darwin, Socrates, Anaxagoras, Theophrastus). 6. ________

7. During the Medieval Period the tendency was to (maintain, discard, substitute for) the authenticity of the old proverbs and superstitions.
7. ________

8. Meteorological instruments had been invented (before, not until after) the time of Erasmus Darwin's weather verses. 8. ________

9. *The Shepherd of Banbury's Rules* were first (collected written, published) in 1744. 9. ________

10. *The Shepherd of Banbury's Rules* were originated by (Mr. Claridge, an unknown, a meteorologist). 10. ________

11. Early almanacs published yearly forecasts based upon (astro-meteorology, folklore, weather signs). 11. ________

12. The appearance of celestial objects as seen through the intervening air (is never, may be, is always) a reliable forecast method.
12. ________

13. "Clear moon, frost soon." This saying (has, has no) scientific basis. 13. ________

14. "The bonnie moon is on her back; Mend your shoes and sort your thack." This saying (has, has no) scientific basis. 14. ________

15. Experiments with thermometers were first undertaken by the ("Academy," "Invisible College," "Florentine Academy," Virgil).
15. ________

16. There are 180 divisions between freezing and boiling points of water on the (Réaumur, Centigrade, Fahrenheit) scale.
16. ________

17. In thermometry the original technical difficulty was in (finding reference points, sealing the tube, obtaining suitable expansible fluids). 17. ________

18. The (Réaumur, Fahrenheit, Centigrade, Absolute) scale was originally graduated from 0 at the boiling point of water to 100 at the freezing point of water. 18. ________

19. The Fahrenheit scale was originally (arbitrarily, scientifically, quasi-scientifically) obtained. 19. ________

20. The principle of the barometer was discovered by (Hooke, Aristotle, Halley, Torricelli). 20. ________

21. (Boyle, Charles, Virgil, Bacon, Darwin) was the author of the *Novum Organum.* 21. ________

22. (Franklin, Halley, von Verulam, Dampier) is known as "the father of dynamical meteorology." 22. ________

23. The period of instrument development in meteorology was between (A.D. 1600-1850, 400-300 B.C., A.D. 1500-1600). 23. ________

24. The psychrometer was invented by (de Saussure, Dalton, Carots, Assmann) in 1825. 24. ________

25. The earliest weather charts were developed by (Ball, Thales, Brandes, Henry). 25. ________

26. In France the first weather service was developed by (Mohn, Le Verrier, Descartes, Kreil) in 1860. 26. ________

27. The development of weather networks mainly depended upon the (invention of the telegraph, development of instruments, training of observers). 27. ________

28. Unified weather networks were first developed in the middle of the (seventeenth, eighteenth, nineteenth) century. 28. ________

29. (Buys Ballot, Henry, Fitzroy) was first placed in charge of the Meteorological Office in London. 29. ________

30. The first weather stations in the New World were established by (Jefferson, Washington, Standish, Franklin). 30. ________

31. The United States Weather Bureau was established under the directorship of the Secretary of (Interior, Agriculture, Navy, War) in 1870. 31. ________

32. The United States Weather Bureau was originally established for (commercial, agricultural, military) purposes. 32. ________

33. In 1890 the United States Weather Bureau was transferred to the directorship of the Secretary of (the Interior, Agriculture, Navy, War). 33. ________

34. The first scientific balloon ascents were initiated by (Bosch, Charles, Dines, Buys Ballot) in 1803. 34. ________

35. The aerometeorograph is carried aloft by (balloons, airplanes, kites). 35. ________

36. The first radiometeorograph was sent aloft by (Bureau and Idrac, Herath and Robitsch, Buys Ballot) in 1927. 36. ________

37. (Dines, Bacon, Le Verrier, Wren) developed the first meteorograph not requiring a clock movement in its mechanism. 37. ________

38. The main ~~exponent of the~~ pressure system of weather forecasting was (Redfield, Dove, Abercromby, Bjerknes). 38. ________

39. The dominant thesis in air mass analysis is that the weather is primarily due to (gradual temperature changes, interactions between air of contrasting properties, pressure differences within an air mass).

39. ________

40. The methods of isentropic analysis are being developed by (Rossby, Solberg, V. & J. Bjerknes, Shaw).

40. ________

CHAPTER II

BASIC CONCEPTS

I. DEFINITIONS

Meteorology is the science of the atmosphere and its phenomena as related to both weather and climate. In keeping with the trend toward division and specialization meteorology, like other sciences, has been subdivided into many branches. This subdivision of meteorology according to the field of human activity served, such as agricultural meteorology, aeronautical meteorology or forest-fire meteorology, is often used for special study. However, the standard divisions as recognized by all students of the subject are as follows:

A. Dynamic Meteorology. In dynamic meteorology the ideal is to apply the tools of mathematical and classical physics to a strict mathematical interpretation of the physical processes of the atmosphere.

B. Synoptic Meteorology. This branch of the science is the most widely used for present-day forecasting. The method consists of collecting many simultaneous observations over a large area, transmitting them by telegraph and radio to central points where they are entered on the weather map and interpreted in terms of the meteorologist's knowledge of all the physical data available. The task of the synoptic meteorologist consists first in analyzing present weather conditions and, then, in extrapolating these conditions and trends into the future for forecasting purposes.

C. Aerology. The term aerology has in the past applied to the study of the free atmosphere. All data gathered from upper air soundings, such as from aerometeorographs, was considered to be its special province. In many meteorological groups the term is now used as a synonym for meteorology. In the United States Navy, officers specially trained in meteorology are called aerological officers and the meteorological stations are called aerological stations. For this service branch, then, aerology and meteorology are synonymous. Most theoretical meteorologists, however, still use the term in reference to the study of the upper or "free" atmosphere.

D. Air Mass and Frontal Analysis. The present method of weather forecasting developed from those methods was pioneered by the Norwegian School of meteorologists. The primary thesis of the method is that overrunning and lifting of air occurs when cold

air masses meet warm air masses. Another axiom of all weather forecasting is that weather in the temperate zones moves from west to east (Fig. 5a).

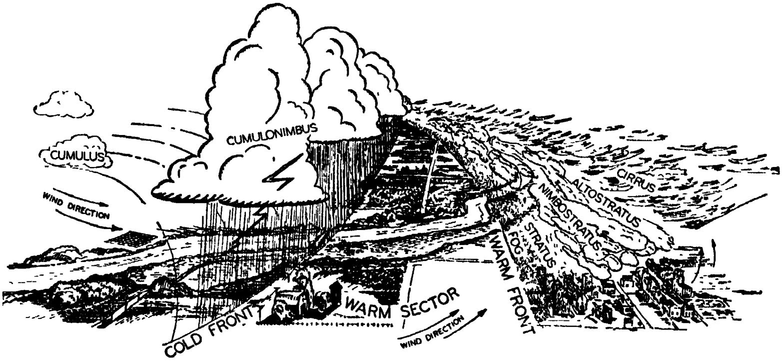


Fig. 5a. Three-dimensional drawing of a frontal system.

1. The Cold Front. When cold air from high latitudes flows southward it pushes the warm air before it and also underruns the warm air mass. As a result the warm air is forced upward so that it cools and its moisture condenses out in the form of clouds and rain or snow (Fig. 5b).

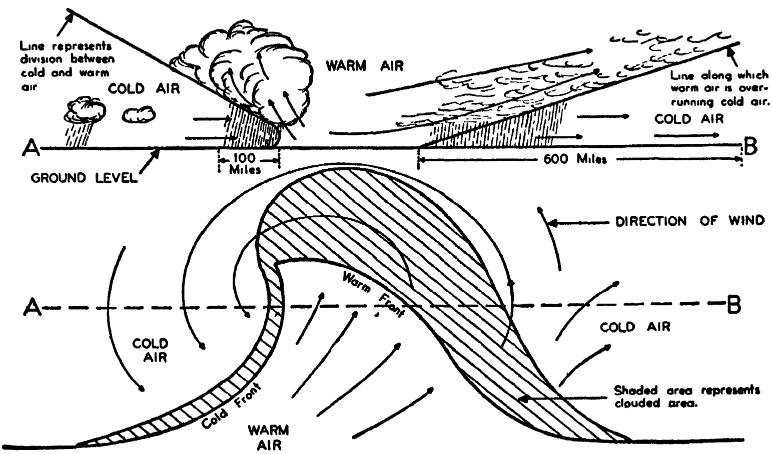


Fig. 5b. Cross-sectional drawing of a frontal system.

2. The Warm Front. As the warm air moves from the low latitudes it overtakes any retreating cold air and flows up over it. In flowing up over the retreating cold air the warm

air is lifted to high altitudes where it cools, condensation takes place and its moisture is precipitated as rain or snow (Fig. 5b).

3. The Occlusion. Due to the general west-to-east movement of the weather cold fronts usually overtake the warm fronts. When such a circumstance occurs the warm air is lifted entirely from the ground.

As the weather has been demonstrated to follow a regular pattern in forming these fronts between air masses of dissimilar properties, and, since each front has its own weather peculiarities, a complete understanding of the method of air mass analysis is indispensable to the modern meteorologist.

II. PHYSICAL AND CHEMICAL PROPERTIES OF THE ATMOSPHERE

A. Composition of Matter. Since meteorology is related to many sciences it is necessary to develop a scientific vocabulary. Many of the terms used are related to the structure of matter. Matter is the name given to all things of a material nature. Men and mice, an airplane and the air through which it flies, all things animate and inanimate are composed of matter. The basic units of matter are submicroscopic particles of positive and negative electricity called protons (positive) and electrons (negative). All electrons are identical as are all protons. While any one particle is like any other, different combinations of these two basic particles will result in different substances with unlike properties. The electrons and protons of tin are identical to those of oxygen. It is the difference in their arrangement that causes the two substances to be so dissimilar. A cathedral or a pigsty might both be made of the same kind of bricks, the dissimilitude of their form would be due to the arrangement.

1. Atoms and Elements. Atoms are composed of electrons (negative particles) and protons (positive particles). There are 92 varieties of atoms. Each different arrangement represents an element. Oxygen, nitrogen, copper, lead, and tin are all elements.

2. Molecules and Compounds. When atoms combine by sharing their electrons the larger aggregates are called molecules. In some cases the atoms of an element may combine with others of their same element. For example, active gases like oxygen, chlorine, nitrogen, hydrogen and bromine may combine with themselves. O (Oxygen atom) + O (Oxygen atom) = O_2 (Oxygen molecule). On the other hand, atoms of different elements combine to form molecules called *compounds*. Thus, water, H_2O, is a compound com-

posed of two atoms of hydrogen combined with one atom of oxygen. Carbon dioxide (CO_2), sugar ($C_{12}H_{22}O_{11}$), sulphur dioxide (SO_2), and table salt (NaCl) are all examples of compounds (Fig. 6).

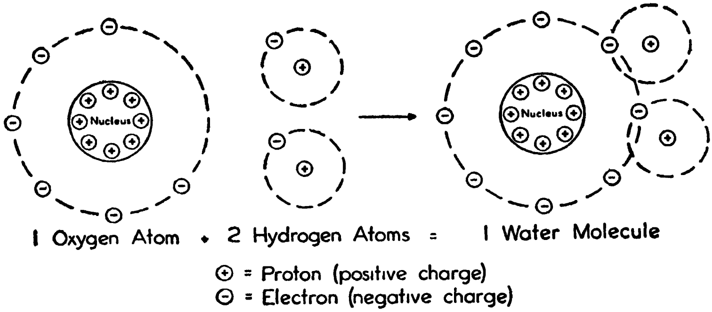


Fig. 6. Chemical reaction.

3. Ions. Atoms of the elements in the uncombined state have the same number of protons as electrons. When an atom gains electrons it becomes negatively charged since it then has more negative particles than positive particles. If an atom loses electrons it becomes positively charged since it then has more protons than electrons. Such charged atoms are called *ions* (Fig. 7).

B. Pressure and Weight. Air has weight and exerts a really tremendous pressure at the earth's surface. At standard pressure our bodies are subjected to a pressure of 14.7 lb. per square inch. Such a prosaic statement usually fails to impress the student but a few implications of this statement will. It would be a feat for some superman to support a weight of over a ton on his chest, yet this is what the average man supports, in terms of atmospheric pressure, on each square foot of his body. 1 sq. ft. = 144 sq. in. 144 times 14.7 = 2116.8 lb. This weight is equal to the weight of 34 cu. ft. of water. One cu. ft. of water weighs 62.4 lb. Since our bodies are surrounded on all sides by an equal pressure, both externally and internally, the great pressure causes no discomfort. The atmospheric pressure at the earth's surface is the result of the weight of the atmosphere itself. The greatest pressure is found at the lowest altitudes. As altitude is gained the atmospheric pressure becomes less. For every 18,000 ft. gain in altitude the pressure is, roughly, one half of its original value. For the same reason that the pressure is greatest at the bottom of the oceans, the pressure is greatest at the bottom of the atmosphere. Obviously this is true because the earth's sur-

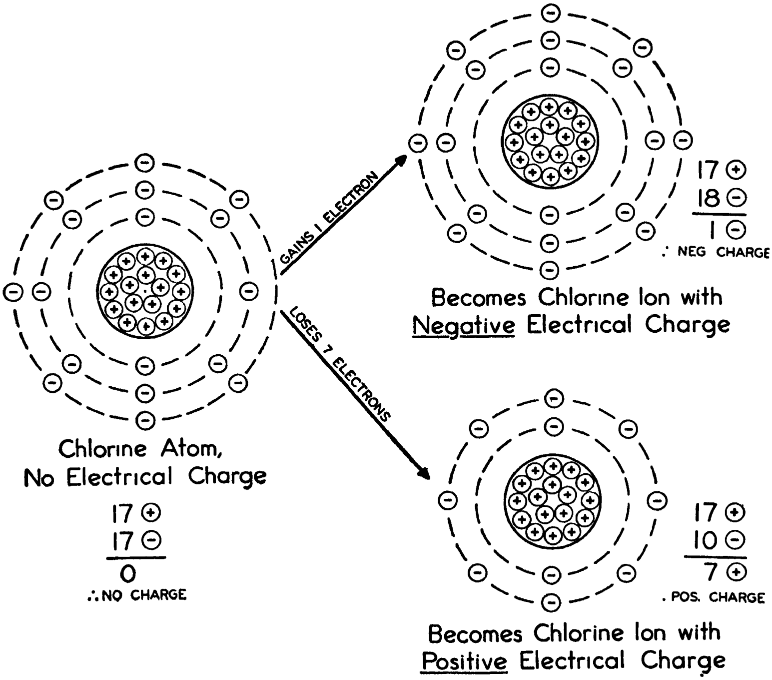


Fig. 7. Method of ionization.

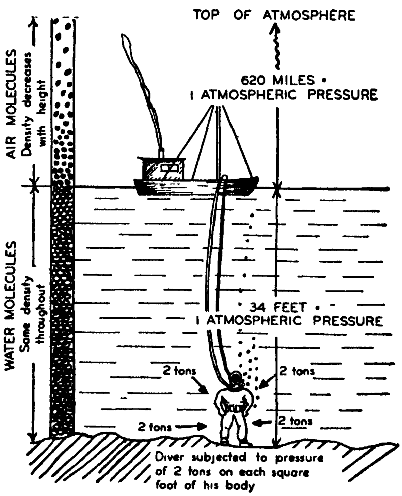


Fig. 8. Density and pressure relationships.

face is comparable to the ocean floor in the atmospheric ocean of air. As elevation is gained pressure decreases because there is less atmosphere overhead. Just as a diver finds the pressure less and less as he approaches the ocean's surface so does an aviator find a decrease of the atmospheric pressure as he flies upward to higher levels (Fig. 8).

C. Density. The density of a substance depends upon the amount of matter in a given volume. In the case of liquids the density cannot be appreciably changed because they are not easily compressed, but in gases the particles (molecules) of which they are composed are more mobile, hence, gases may be compressed. Thus, the water at the bottom of the ocean is of nearly the same density as the water at the surface while, on the other hand, at the earth's surface the atmosphere is compressed by the weight of the atmosphere above it and has a greater density. As an aviator flies upward he finds that not only the pressure of the atmosphere decreases but also its density. In physics these relationships are expressed in the following manner (Fig. 9).

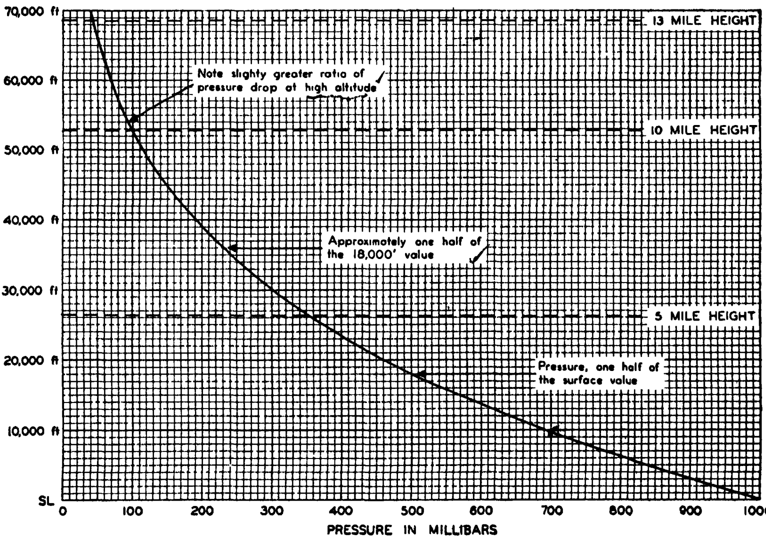


Fig. 9. Up to 10,000 ft. there is approximately a 1-in. change in atmospheric pressure for each 900-ft. change of elevation.

1. Density = weight/volume, (more correctly) density = mass/volume. For example, 1 cu. ft. of water weighs 62.4 lb., while 1 cu. ft. of mercury weighs 848.64 lb. Hence, the density of water is 62.4 lb. per cubic foot and that of mercury is 848.64 lb. per cubic foot.

2. Specific gravity = density of substance/density of water. Specific gravity of mercury = 848.64/62.4 = 13.6. Thus it can be seen that a given volume of mercury is 13.6 times as heavy as an equal volume of water. In the metric system the density values and the numbers representing the specific gravity are the same, as one gram of water has a volume of one cubic centimeter at 4° C. Density of water = 1 gram/1 cc = 1 gram per cc. Density of mercury = 13.6 grams/1 cc = 13.6 grams per cc. Specific gravity of mercury = 13.6 (density of mercury)/1 (density of water) = 13.6. Whereas 1000 cc of water weigh 1000 grams an equivalent volume of air weighs only 1.29 grams at sea level and O° C. However, the average depth of the ocean is only about two and one-third miles while the atmosphere extends upward to over 600 miles.
3. Effect of Pressure on Density. D/P = D′/P′. First density/first pressure = second density/second pressure. 1.29 grams per liter/14.7 lb. per square inch = D′/7.35 lb. per square inch. D′ = .645 gram per liter. From this example it may be seen that the density of the air is directly proportional to the pressure. Thus, at 18,000 ft. the weight of a given volume of air is only about one half its surface value.

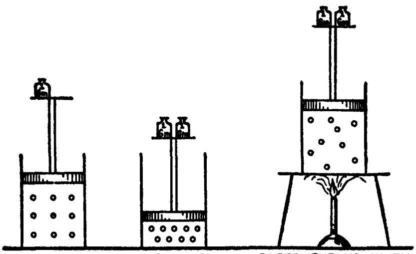


Fig. 10. Physics of gases.

4. A given volume of air has a certain density because it contains a certain amount of matter in the form of molecules. When the air is heated these molecules of which the air is composed increase their speed and, if allowed, the air will expand. Since the same number of molecules then occupy a larger amount of space (greater volume) the density (weight per unit volume) is decreased. *Heating air causes it to expand and become lighter.* Light (warm) air

will float on heavy (cold) air; thus, it is commonly said that warm air rises. Actually a parcel of warm air rises because it is displaced and forced upward by the surrounding air which is cooler and more dense. This parcel of warm air will continue its upward motion until it reaches a level where the density of the surrounding air is just equal to its own density (Fig. 10).

5. Following is a short table of comparative densities of some representative substances given in grams per cubic centimeter at 20° C.

Aluminum	2.65
Copper	8.93
Gold	19.32
Iridium	22.41
Iron	7.86
Lead	11.37
Water (at 4° C.)	1.0000
Air	0.001293
Hydrogen	0.000899
Oxygen	0.001429

COMPOSITION OF PURE AIR AT SEA LEVEL

CONSTITUENT	VOLUME PER CENT			
	Water Vapor Content			
	0%	0.2%	0.9%	2.6%
Nitrogen	78.08	77.9	77.4	76.05
Oxygen	20.95	20.9	20.8	20.4
Argon	0.93	0.93	0.92	0.91
Carbon Dioxide	0 03			
Hydrogen	less than 0.01			
Neon	0.0018			
Helium	0 0005			
Krypton	0 0001			
Xenon	0.000009			
Ammonia	0 0000026			
Ozone	0 000002			
Hydrogen Peroxide	0 00000004			
Iodine	trace			
Radium Emanation	trace			

D. Chemical Composition. The atmosphere is a mixture of gases. This mixture is found to be fairly constant in chemical composition when samples of it are taken at any place in the earth's atmosphere. Roughly, the atmosphere is four fifths nitrogen and

one fifth oxygen. All the other gases are found in only small amounts. Certain of the constituents, such as water vapor, vary with changing conditions.

Distribution of Oxygen with Height.

The pressure of the atmosphere at standard conditions at sea level is 14.7 lb. per square inch. On a barometer this pressure is represented by a mercury column 29.92 in. in length or 760 mm or by 1013.25 (mb). (One inch of mercury = 33.86 mb.) Of the various gases of the atmosphere oxygen is the life sustaining element. For the purpose of high-altitude flying many studies have been made of the distribution of this vital element with altitude. At sea level about 200 mb of the total pressure of 1013.25 mb is contributed by the oxygen content of the air. When this concentration of oxygen is available the physiological reactions of a person are normal. When an aviator is flying at 10,000 ft. the atmospheric pressure has decreased to 700 mb and that of the oxygen to 140 mb. With no oxygen equipment the aviator's physiological reactions would be subnormal. At an altitude of 24,000 ft. the atmospheric pressure would be 400 mb, the oxygen pressure only 80 mb, and the pilot would be unconscious.

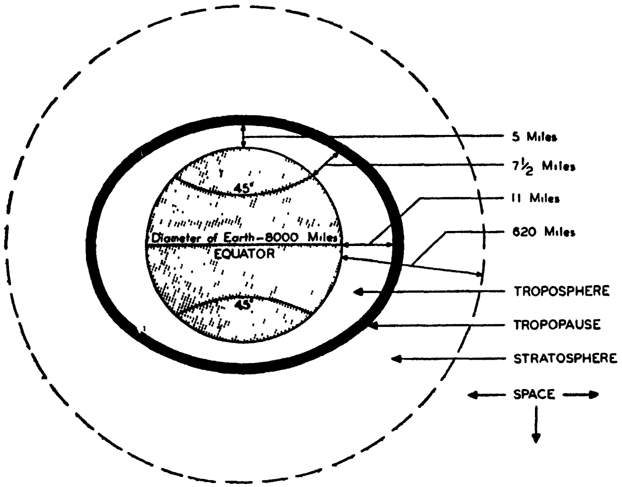


Fig. 11. Vertical structure of the atmosphere.

III. THE VERTICAL STRUCTURE OF THE ATMOSPHERE

A. Height of the Atmosphere. Due to compression, one half of the weight of the atmosphere lies below the 18,000-ft. level. The

greatest volume of the atmosphere is above this level. Meteors or "shooting stars" have been observed up to heights of 200 miles. Since meteors only become visible when heated to incandescence by the friction of the atmosphere the air must be fairly dense at even this great altitude. The Auroras, which are believed to be electrical discharges in rarefied gases, have been observed by photographic means to altitudes of 620 mi. The height of this phenomenon is believed to represent the extreme outer limits of the earth's atmosphere. (Fig. 11)

B. Troposphere. The layer of air nearest to the earth's surface is called the troposphere. The depth of the troposphere varies with the seasons. The average depth of the layer is 5½ miles at the poles, 7½ miles over the temperate zones and 11 miles over the equator. Due to cooling effects of expansion the coldest place in the earth's atmosphere is found at the top of the troposphere over the equator. Characteristically, throughout this layer of the atmosphere all the vertical air currents are found. This is also the layer of clouds, precipitation (rain, snow, etc.) and weather. As altitude is gained through the troposphere the temperature usually decreases. The average rate of temperature drop with gain in altitude is 0.55° C. per 100 meters.

C. Tropopause. Between the lowest layer of the atmosphere and the outer layer there is a transition zone known as the tropopause. This zone is characterized by the fact that there is no change of temperature with altitude. No convective currents, clouds, or weather are found in the tropopause.

D. Stratosphere. Above the tropopause the stratosphere extends upward to outer space. As in the tropopause no convective currents, clouds, or weather are found in the stratosphere. Recent experiments have demonstrated that there is a pronounced gain in temperature with altitude above the 15-mile elevation. At 18-miles' altitude the temperature has risen from — 80° C. to — 50° C. while at 31 miles the temperature is 70° C.

Ionosphere. In the stratosphere the number of free ions of air are found concentrated in several strata. Since many interesting electrical phenomena take place in these layers they are often classified together as the *ionosphere*. The aurora borealis and aurora australis occur at high latitudes in these layers. In addition, the ionized layers reflect and absorb radio waves and absorb certain wave bands of the sun's energy. The layers of the ionosphere are classified as follows:

a. The D layer is found at an altitude from 18 to 28 miles. It reflects and absorbs long-wave radio transmission.

b. The E, or Heaviside-Kennelly, layer is the ionized layer between 55- to 75-miles' altitude. Radio waves of 300 to 400 meters are reflected by this layer.

c. At an altitude of 135 to 162 miles the F, or Appleton, layer reflects short radio waves and absorbs energy from the ultra-violet wave band of the sun's energy.

TEST QUESTIONS ON BASIC CONCEPTS

1. The study of the upper air is (dynamic meteorology, aerology, synoptic meteorology). 1. ________

2. When cold air underruns warm air the discontinuity line is called a(n) (cold front, occlusion, warm front). 2. ________

3. When the warm air is lifted entirely from the ground the discontinuity line is called a(n) (cold front, occlusion, warm front). 3. ________

4. The smallest negative particles of matter are the (electrons, protons, atoms, molecules). 4. ________

5. The smallest positive particles of matter are (electrons, protons, atoms, molecules). 5. ________

6. The smallest particles having the properties of elements are (electrons, protons, atoms, molecules). 6. ________

7. The smallest particles having the properties of compounds are (electrons, protons, atoms, molecules). 7. ________

8. When atoms are unbalanced electrically they are called (protons, electrons, neutrons, ions, positrons). 8. ________

9. Anything occupying space and having mass is called (density, volume, matter, compounds, molecules). 9. ________

10. In the following list check the element (sugar, brass, table salt, aluminum, water). 10. ________

11. Atoms become charged positively by (gaining, losing) (electrons, protons, neutrons). 11. ________

12. Liquids are (easily compressible, difficultly compressible). 12. ________

13. Gases are (easily compressible, difficultly compressible). 13. ________

14. The atmospheric pressure at sea level is (34 lb. per square inch, 29.92 lb. per square inch, 14.7 lb. per square inch). 14. ________

15. The pressure is decreased by one half for every (1800-ft., 36,000-ft. 18,000-ft., 10,000-ft.) gain in altitude. 15. ________

16. The total force exerted by the atmosphere on the surface of an evacuated tin can 4x8x12 in. at sea-level pressure is (5474.8 lb., 940.8 lb., 384 lb., 11890.4 lb., 5174.4 lb.). 16. ________

17. The volume of 312 lb. of water is (10 cu. ft., 5 cu. ft., 4 cu. ft., 6 cu. ft.). 17. ________

18. The weight of 2 cu. ft. of an unknown substance is 980.93 lb. Its specific gravity is (11.37, 7.86, 8.93, 2.65). 18. ________

19. About 4/5 of the atmosphere by volume is (oxygen, carbon dioxide, xenon, nitrogen). 19. ________

20. At sea-level pressure about (300 mb, 200 mb, 375 mb, 500 mb) of the total pressure is due to the oxygen content. 20. ________

21. The atmosphere is believed to extend to a height of (200 miles, 162 miles, 400 miles, 620 miles). 21. ________

22. The Auroras are electrical discharges occurring in the (troposphere, stratosphere, tropopause). 22. ________

23. The layer of air in which weather occurs is the (troposphere, stratosphere, ionosphere, tropopause). 23. ________

24. The transition zone of the atmosphere is the (troposphere, stratosphere, ionosphere, tropopause). 24. ________

25. The temperature increases with gain of altitude in the (troposphere, stratosphere, tropopause). 25. ________

CHAPTER III

ATMOSPHERIC THERMAL RELATIONSHIPS

I. THE NATURE OF HEAT AND TEMPERATURE

The atmosphere is primarily a heat engine. All the multiplicity of complex changes occurring constantly in the gaseous envelope surrounding the earth are possible because of an unfailing energy source, the sun. If the sun's energy were not continually available the atmosphere would freeze and life would cease to exist on a frigid world covered with drifted heaps of frozen gases.

A. Heat and Temperature. Heat is molecular energy. If all the molecules in a body were to cease their movement the temperature of that object would drop to Absolute zero and its heat content would be zero. The amount of heat in any body depends upon the mass of the body and the degree of movement of its molecules. For example, an ordinary parlor match when lit burns at a high temperature (500° C.) yet, although it will sear a person's finger, its total heat content is not great enough to melt an ice cube. On the other hand, an ice cube of similar mass would be melted if it were placed in a pail of cold water at a temperature of only 10° C. *Temperature represents the average level of the thermal energy of a mass.* Small objects, even though they may be heated to high temperatures, cool rapidly because their heat content is small although the degree of heat is high. (Fig. 12)

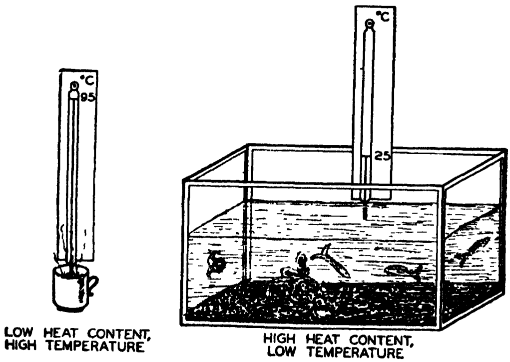


Fig. 12. Comparison of heat and temperature.

B. Measurement of Heat. Heat is measured by the effects it produces.

1. The gram calorie is the amount of heat necessary to raise one gram of water one degree Centigrade.
2. The kilogram calorie is the amount of heat required to raise one kilogram (1000 g) of water one degree Centigrade.
3. The British thermal unit, or B.t.u., is the amount of heat required to raise one pound of water one degree Fahrenheit. One B.t.u. is equal to 252 gram calories. One pound of coal liberates between 11,000 to 16,000 British thermal units. One pound of gasoline liberates 19,000 British thermal units or about 114,000 British thermal units per gallon.

C. Specific Heat. Certain substances heat more quickly than others. A substance that heats quickly will also cool quickly. When dry land and the ocean are both exposed to equal amounts of solar radiation, the dry land will heat much more quickly and to a higher temperature. (At night the land will cool more quickly than the water. The heat required per degree rise of temperature varies as the mass of the substance times a constant whose value is determined by the nature of the substance heated.) At 15° C. one gram calorie is required to raise the temperature of one gram of water one degree Centigrade; hence, the specific heat of water is one. The specific heat of a substance is the number of gram calories required to raise the temperature of a gram of the substance one degree Centigrade. An amazing fact is that of all ordinary substances, except hydrogen, water has the highest specific heat. Following are some comparative values for specific heat:

Ice at 0°	= 0.502
Steam at 100°	= 0.421
Mercury	= 0.0331
Iron	= 0.114
Crown glass	= 0.16
Ordinary soil	about 0.25

D. Measurement of Temperature.

1. Temperature is now commonly measured on three scales, namely: Centigrade, Fahrenheit, and Absolute. The Fahrenheit scale is used popularly in the United States and Great Britain. In meteorological work the Fahrenheit scale is used to indicate the temperature on teletype sequence re-

ports. The Centigrade and Absolute scales are used for most scientific work. (Fig. 13).

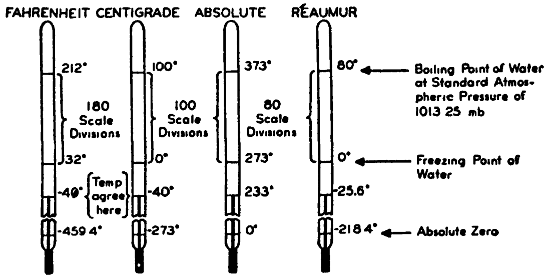


Fig. 13. Comparison of thermometer scales.

F. — 32 × 5/9 = C. or F — 32/1.8 = C. C. × 9/5 + 32 = F or C × 1.8 + 32 = F
F. — 32 × 4/9 = Réaumur R × 5/4 = C. C. × 4/5 = R
R × 9/4 + 32 = F. Centigrade + 273 = Absolute
Fahrenheit + 459.4 = Fahrenheit Absolute

2. Since the Centigrade, Fahrenheit and Absolute scales are all used in meteorological work, it often becomes necessary to convert one scale to the other. The conversion may be accomplished as follows:

a. Centigrade to Fahrenheit. Water boils at 212° F. or 100° C.; hence, these two temperatures must be equivalent. Water freezes at 32° F. or 0° C. There are just 100 divisions of the Centigrade scale to represent this range between freezing and boiling points of water. On the Fahrenheit scale, however, there are 212 minus 32 or 180 scale divisions to represent the same range. Then, one division on the Centigrade scale must equal 1.8 divisions on the Fahrenheit scale. For example, 100° C. × 1.8 = 180°. At the freezing point of water the Fahrenheit scale is already 32 degrees above its zero so 32° must be added to the above. Hence, 100° C. × 1.8 + 32 = 212° F. As a formula this conversion may be expressed as: C. × 1.8 + 32° = F.

b. Fahrenheit to Centigrade. Applying the above reasoning in the reverse order 32° is first subtracted and the resultant difference is divided by 1.8. For example, 212° F. — 32° = 180°/1.8 = 100° C. When working with minus temperatures the addition of 32° is performed algebraically. Thus, — 40° F. — 32° = — 72/1.8 = — 40° C. As a formula this conversion may be expressed as: F. — 32°/1.8 = C.

c. Centigrade to Absolute. Gases, at constant pressure, expand 1/273 of their volume at zero for each rise in temperature of one degree Centigrade. Since the converse of this is true for the lowering of temperature below zero degrees Centigrade, the Absolute zero was determined to be — 273° C. (This is the theoretical value, the actual value is believed to be slightly lower, — 273.13° C.) If the Absolute zero is — 273° C. then 0° C. = 273° Absolute. To change any Centigrade temperature to Absolute, the Centigrade temperature is merely added algebraically to 273. For example, 20° C. + 273 = 293° Absolute. — 30° C. + 273 = 243° Absolute. Obviously, there are no negative Absolute temperatures as the Absolute zero is the temperature where, theoretically, all molecular motion ceases and no heat exists. There could be no colder temperature than no heat at all.

d. Fahrenheit to Absolute. One degree on the Centigrade scale is equal to one degree on the Absolute scale, hence, one degree on the Absolute scale must be equal to 1.8 degrees on the Fahrenheit scale. Between the Centigrade zero and the Absolute zero there are 273 Centigrade or Absolute scale divisions. 273 of these divisions are equal to 273 × 1.8 = 493.4 Fahrenheit scale divisions. However, zero on the Fahrenheit scale is 32 Fahrenheit degrees below the Centigrade zero. Hence, Absolute zero on a Fahrenheit thermometer would be at 493.4 — 32 = 459.4 F. To change Absolute to the Absolute Fahrenheit equivalent it is only necessary to add the Fahrenheit temperature algebraically to the conversion factor 459.4. For example, 20° F. = 459.4 + 20 = 479.4° Fahrenheit Absolute. — 30° F. = 459.4° — 30 = 429.4° Fahrenheit Absolute.

E. Methods of Heat Transfer

1. Conduction is the transfer of heat by direct contact. This means of thermal transfer is of secondary importance in atmospheric phenomena since the air is a poor conductor. Conduction is only important in heating layers of air in direct contact with the ground.

2. Radiation is the transference of energy in straight lines through space not occupied by matter or through matter without its being affected. Radiation is the means whereby

energy is transferred through space without the aid of a material medium. The atmosphere is transparent to most of the radiation of the sun, but some wave lengths are partially absorbed.

3. Convection is the transfer of energy by means of currents set up in fluids. This means of transfer is of prime importance in creating weather in the troposphere. The heating by conduction of air in direct contact with the warm earth causes this air to expand and decrease in density. Because of its consequent increased buoyancy this warm air is then forced to rise in small masses through the surrounding cooler air. As these warm air masses ascend, they expand under the lower pressure around them, thus cooling. This process of "convection" is compensated for by the sinking of the denser, cooler air surrounding the rising, warm air. Thus, it may be said that convection is a means of transporting heat upward in the atmosphere from the earth's surface by the actual bodily ascent of air which has been warmed by contact with any part of the surface warmer than the air layer immediately above it. The above process represents true *thermal convection.* When air is forced to rise by blowing against objects in its path the process is known as *mechanical convection.*

4. Absorption of radiant energy by matter results in the transformation of one form of energy to another kind. An example is the absorption of short-wave radiation by the ground and the reradiation of long-wave radiation, or the giving off of heat energy.

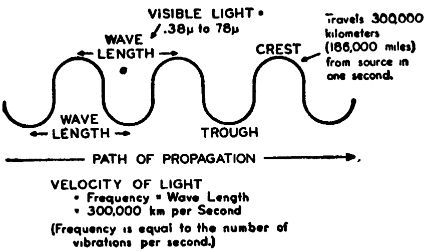


Fig. 14. Propagation of light by transverse waves.

II. *THE ELECTROMAGNETIC SCALE OF ENERGY*

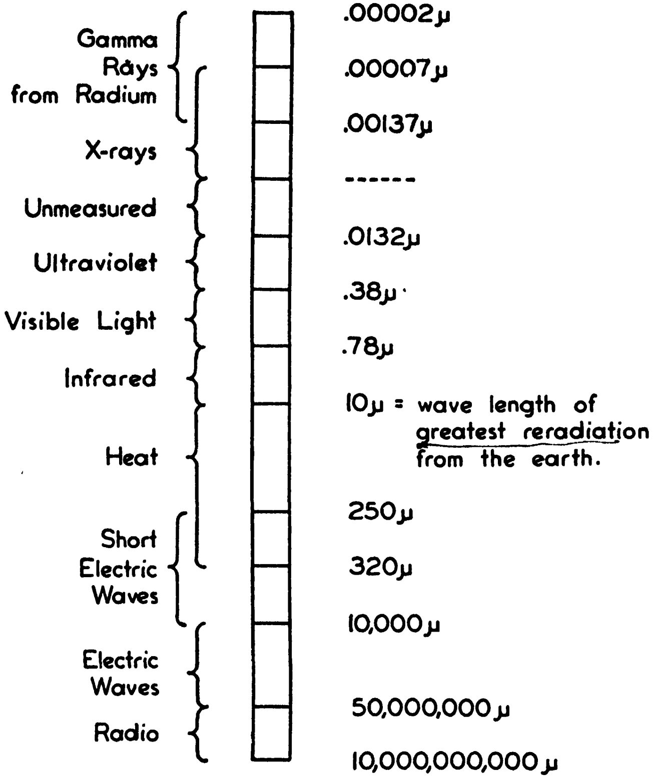
Light and heat waves are both included in the scale of electromagnetic energy. Many and varied are the properties of the energy types ranging from gamma rays to radio waves. Gamma rays will penetrate a foot of lead while ultra-violet rays on the same

scale are highly absorbable even by transparent media. The wide range in the properties is due to frequency and wave-length differences. (Fig. 14)

1. Wave Length. The different energy types on the electromagnetic scale have a common property inasmuch as they are all transverse waves. Transverse waves vibrate at right angles to their path of motion. The wave length is the distance from equal phases of one wave to equal phases of the next. Thus, the wave length might be measured from the trough of one water wave to the trough of the next, or, from crest to crest. Electromagnetic waves are measured by using very small units. One unit used is the micron, abbreviated μ (mu). This unit is equal to 1/1000 millimeter or 1/1,000,000 meter. Another unit is the millimicron which is 1/1000 micron. Still another unit is the Angstrom unit equal to 1/10,000 micron.
2. Frequency. The speed of electromagnetic energy is 186,000 miles per second or 300,000 km per second. Since in all wave motion the velocity = frequency $\times$ wave length, and velocity is constant, if the wave length is shortened the frequency must be increased. For example, when a light wave is generated the first wave crest has moved 186,000 miles from the source in one second. If the distance from the crest of one wave to the crest of the next (wave length) is some microscopically small figure like .00038 of a millimeter it becomes obvious that an extremely large number of these waves will be required to cover the enormous distance of 186,000 miles or 300,000 km. Hence, the shorter the wave length, the greater must be the frequency.
3. Visible Light. The range of visible light is included in the wave band from 0.38μ to 0.78μ. The colors range from the violets at the short-wave end to red at the long-wave end. The colors in correct order of frequency from long wave to short wave may be remembered as ROY G. BIV. They are red, orange, yellow, green, blue, indigo and violet.
   a. Ultraviolet (.013μ to .38μ). The wave band just below that of the visible range is that of the ultraviolet. Although the energy of this band is invisible it stimulates chemical activity. It is the energy in the ultraviolet that causes sunburn, as well as the formation of vitamin D under our skins by the stimulation of the ergosterol. In refraction, violet and ultraviolet waves are bent more than the red and infrared.

b. Infrared (.78μ to 10μ). The energy band just above the visible reds is the infrared. This band is akin to the heat wave band (10μ to 250μ) and produces heating effects. Pictures may be taken in a dark room by using special infrared sensitive film. Reradiated energy from the earth is at its maximum at 10μ.

Scale of Electromagnetic Energy



III. *SOLAR RADIATION*

A. Sources of Heat. In meteorology the sun is considered to be the only significant source of heat since on a day when the average temperature is 75° F. all other sources contribute only 0.25° F. The surface temperature of the sun is about 10,300° F. Other sources include starlight, light from the planets, our moon, and heat from the interior of the earth. Energy received from the sun is called *insolation*.

B. Nature of Solar Energy.

1. The sun radiates electromagnetic waves of short wave length including those of visible light. These waves are similar in quality to radio and X-rays, being shorter than the former and longer than the latter.
2. Visible light varies from .38μ in the violet to 0.78μ in the red. Infrared ranges from .78μ to 10μ where there is an overlap with the very short heat waves. Ultraviolet ranges from .38μ to 0.013μ where there is an overlap with the "soft X-rays."
3. The limits of solar energy lie between 0.2μ to 3μ. This is distributed as follows:
   a. 5% below .38μ (ultraviolet)
   b. 43% between .38μ to 0.78μ (visible spectra).
   c. 52% above 0.78μ.

C. The Solar Constant. The rate at which the sun sends out radiant energy is measured by observing the intensity of radiation at the earth's surface and by calculating the intensity at the top of the earth's atmosphere. The average amount of solar energy received per minute at the top of the atmosphere on an area of one square centimeter is 1.94 calories. (1 sq. cm = 0.155 sq. in. This would raise the temperature of one pound of water 7.15° F. per minute if incident on one square foot.) This constant fluctuates slightly due to solar disturbances.

IV. *TERRESTRIAL RADIATION AND THE HEAT BALANCE OF THE ATMOSPHERE*

A. Factors Affecting Insolation. Insolation is dependent on the following factors:

1. Season.
2. Directness of the sun's rays (latitude).
3. Nearness of the sun (91,300,000 miles in January; 94,-500,000 miles in July). Causes 7% variance in the intensity of rays. (Fig. 15)
4. Nature of the atmosphere.
5. Duration of insolation.

B. (Heat Balance. There is a *heat balance* in the earth's atmosphere. If the same amount of heat did not pass out into space as was received by the earth it would become progressively hotter or colder. Much of the outgoing radiation from the earth is of the long-wave type beyond the visible spectrum.)

C. (Temperature and Altitude. In the troposphere the principal kind of energy to be absorbed is the outgoing terrestrial radiation. The absorption of incoming solar radiation is secondary. Hence, the conditions of radiative equilibrium demand a decrease

of temperature with height. The expansion of rising air also contributes to the cooling effect with gain of altitude.

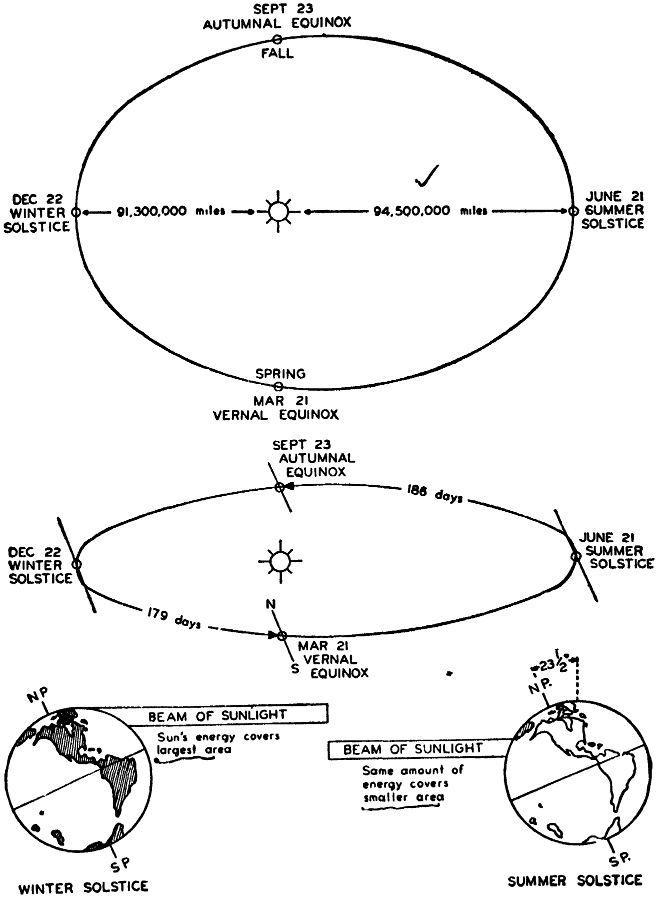


Fig. 15. The seasons.

In the Northern Hemisphere the earth is actually farther from the sun in the summer than in the winter. The sunlight is warmer because the tilt of the earth's axis causes the sun to strike the earth's surface at an angle nearer to the vertical than in the winter.

V. *DEPLETION OF SOLAR RADIATION IN THE ATMOSPHERE*

A. About one two-billionth of the total radiation of the sun is incident on (strikes) the upper limits of the earth's atmosphere. This incident energy is either reflected, transmitted, diffused or absorbed. The *permanent* gases composed of nitrogen, oxygen,

hydrogen and the "inert" gases absorb some of this solar energy. However, the greatest amount of absorption and diffusion is due to the variables. The *variables* consist of H_2O vapor 0 to 4% by volume, carbon dioxide 0 to 0.03%, ozone and the "solid impurities" such as dust, smoke, chemicals, microörganisms and clouds. The permanent gases exist in nearly the same proportions at all heights; the variables show a rapid decrease with altitude. The variables serve to deplete solar radiation by scattering, reflection, and absorption. (Fig. 16)

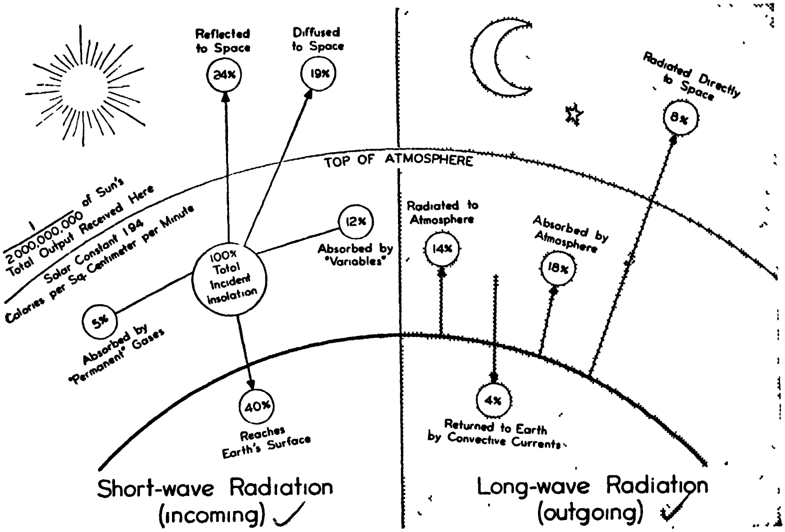


Fig. 16. Heat balance of the atmosphere.

B. On the basis that the average cloudiness is 52%, about 43% of the incident solar energy is reflected back into space before it has penetrated any more than the higher levels of the atmosphere. Of this 43% about 19% is due to diffusion in the upper atmosphere. This diffused light results in the phenomenon of the blue sky and is known as *sky radiation.*

C. Of the remaining 57% of the solar radiation about 12% is absorbed by the water vapor in the atmosphere, 5% is absorbed by permanent gases, dust and clouds. 40% of the total incident solar energy finally reaches the ground to be absorbed or reflected from the surface.

D. Varying amounts of energy incident on the earth's surface are reflected. The amount of reflection depends on the nature of the material at the surface. Snow reflects 70 to 80%. Rock and

dry mold reflects about 13%. Wet mold reflects 9%. Grass reflects from 10 to 33%. When the sun is at 47° from horizon a water surface will reflect 2% of incident sunlight. When the sun is 5.5° above the horizon 71% of the incident sunlight will be reflected. The earth reradiates solar energy as heat waves with wave lengths between 3μ to 50μ. The maximum intensity of reradiated energy is at 10μ.

E. The previous figures assume a 52% covering of the sky with clouds. When the sky is completely overcast the upper surfaces of the clouds may reflect back as much as 80% of the incident sunlight.

F. The absorption and reradiation by water vapor is important in the study of the heat balance of the atmosphere. Water vapor is the main constituent of the atmosphere capable of absorbing light and emitting it as long wave-heat radiation. Surface radiation is largely suppressed by the blanket of water vapor lying immediately above the surface. Hence, it is only from layers well above the surface of the earth that an appreciable quantity of radiation escapes into space. Near the equator the incoming solar radiation exceeds that lost to space. From latitude 38° to 90° during the yearly cycle of seasons a greater amount of radiation is lost to space than is received. The primary circulation of the atmosphere is largely dependent on the above facts.

G. Absorption of Short- and Long-wave Radiation.

1. Dry air absorbs short-wave radiation poorly. Moist air absorbs short-wave radiation better. During the winter the smoke and dust of some large cities will absorb over 50% of the incoming short-wave solar radiation.
2. Since the water vapor transmits short-wave radiation, and absorbs long-wave radiation, a phenomenon known as the *greenhouse effect* results. Incoming solar radiation is largely transmitted (allowed to pass). Outgoing terrestrial long-wave radiation is absorbed. Most of the absorbing water vapor is concentrated in the low altitudes. As the earth is the radiating source of the long-wave radiation and the absorbing media is at a relatively low altitude, a "blanket" or greenhouse effect results. It is partly due to the greenhouse effect that the air becomes colder with a gain in altitude in the troposphere.
3. In the stratosphere most of the heating of the air results from absorption of incoming short-wave radiation. Hence, an inversion of the normal vertical temperature gradient of the troposphere is found in the stratosphere, with the air being heated to a greater extent by the incident short-wave radiation as altitude is gained.

H. Heating Effects.

1. Summer. In the summer on cloudless days, terrestrial radiation and resulting convection by heating from the ground warm the first 10,000 ft. of the atmosphere considerably. At night (since the soil is a good radiator) the ground radiates heat rapidly to outer space if there are no clouds to absorb the escaping energy. At the levels near the ground superheating will occur in the daytime resulting in strong lapse rates. At night supercooling may give rise to inversions and the formation of radiation fog.
2. Winter. In the winter the ground heats but little due to the reflection of the snow. Inasmuch as the snow covering prevents the ground from absorbing heat, if clouds are lacking and the water vapor content of the air is low, the lower layers of the air will cool quickly at night. If a cloud layer forms the following day, and protects the ground from further heating, a temperature inversion formed in the above manner may persist for several days. Under other circumstances when there is no snow covering the ground the heat will radiate into space more quickly if there is no cloud covering. In these conditions when the clouds cover the sky at night they absorb much of the terrestrial radiation and emit short-wave length radiation at their own temperature. Such varying conditions as those just described exercise marked influence on the vertical temperature gradient (change of temperature with altitude).
3. Land. Over the land the air near the ground is cooled at night by contact with the rapidly cooling ground. In the daytime the air near the ground is superheated. Hence, there is a rather wide range of temperature variation occurring daily over the land. This effect is due to the facts that ordinary earth is a good absorber, a good radiator, and has a low specific heat. (Fig. 17)

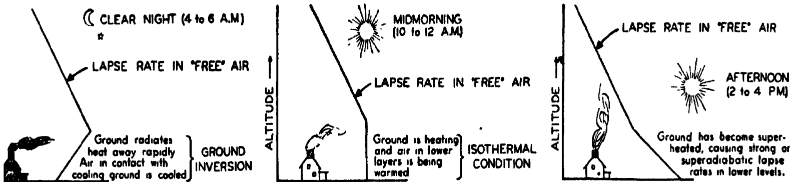


Fig. 17. Diurnal variation of lapse rates over the land in clear weather.

4. Sea. Over the sea very little surface temperature variation occurs. Water has a high specific heat. Water is also per-

meable to sunlight; hence, it is heated to greater depths than land and, consequently, takes much longer to change in temperature. Due to its high specific heat water does not cool rapidly at night. Hence, temperatures over the ocean remain fairly constant and exhibit only slight diurnal changes. This effect is important in modifying many of the weather elements. (Fig. 18)

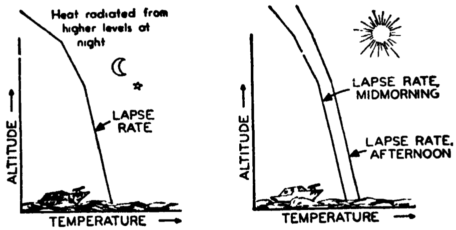


Fig. 18. Lapse rates over the ocean.

(The temperature of the ocean remains nearly constant both night and day Since there is little surface heating (less than .55° C) or cooling the air temperature remains nearly constant in the lower levels.)

VI. *ADIABATIC RATES:*

Adiabatic rates are the rates at which individual parcels of air, moving independently, change their temperature with vertical displacement. When a small parcel of air is displaced upwards it expands and cools. Air brought down from aloft contracts and heats. These heating and cooling processes go on without the transfer of energy from, or to, the surrounding atmosphere. Such processes resulting in temperature changes without the addition or loss of energy to outside sources are called *adiabatic*. (Fig. 19)

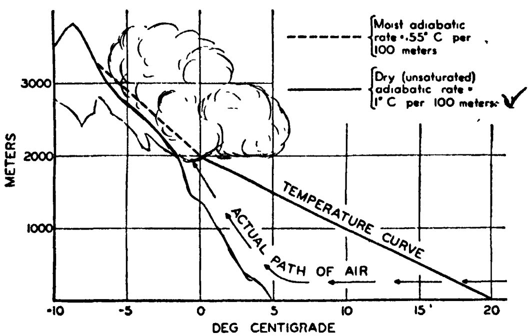


Fig. 19. Adiabatic rates.

(When air rises up through the atmosphere it cools first at the dry adiabatic rate (1° C. per 100 meters) and then at the moist adiabatic rate (.55° C. per 100 meters) after condensation. If air is brought down from aloft it will heat at the dry adiabatic rate.)

A. Dry Adiabatic Rate:

When parcels of air rise, their molecules do work against the pressure of the outside air as the parcel expands. The energy required for this work is drawn from the parcel. As a result the temperature of a rising parcel of air falls at a steady rate of approximately *1° C. per 100 meters.* (1° C. per 102.39 meters.) If the parcel is forced downward the temperature will rise at the same rate. This rate of change in the temperature of an unsaturated parcel of air as it gains or loses altitude is known as the *dry adiabatic rate.*

B. Moist Adiabatic Rate:

When rising air becomes saturated with water vapor it cools at a new rate due to the energy made available by the heat of condensation released. This new rate of cooling of saturated air is known as the *moist adiabatic rate.* The *mean* moist adiabatic rate = *.55° C. per 100 meters.* Moist adiabatic rates may vary from 0.4° C. per 100 meters to nearly the dry adiabatic rate.

VII. VERTICAL TEMPERATURE DISTRIBUTION (LAPSE RATES):

The change of temperature per unit vertical distance as one changes altitude through the atmosphere is known as the *lapse rate.* (Fig. 20a and b)

A. Normal lapse rate:

Through the first 18,000 ft. (5500 meters) of the troposphere the normal or average decrease of temperature with altitude is .55° C. per 100 meters. (.3° F. per 100 ft.) (Under these conditions if the temperature at the surface were 20° C. at 1000 meters the temperature would be 14.5° C.

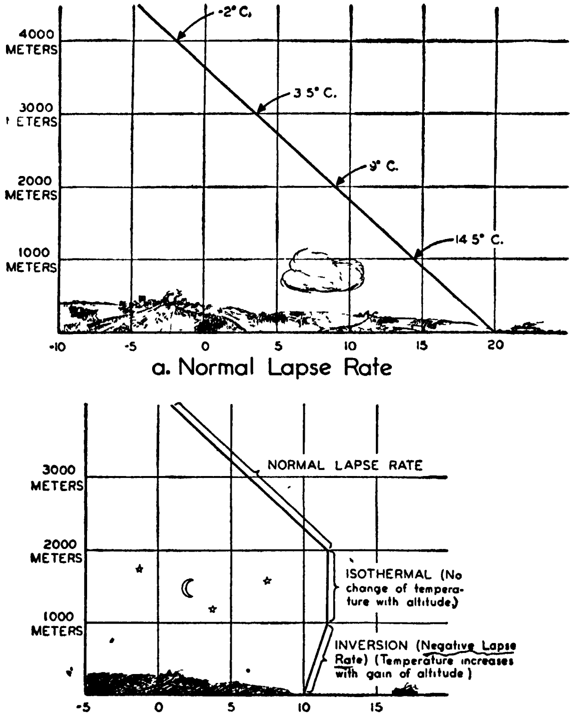
B. Inversions:

Inversions are listed as *negative lapse rates.* 0.8° F./100 ft. (increase in temperature with height) is recorded as a lapse rate of —0.8° F./100 ft. Inversions may occur in close vicinity to the ground in low lying places at all seasons. In the winter when snow covers the ground inversions may become quite deep and persistent. In polar regions inversions sometimes extend up to as high as 2000 meters with temperature increases of as great as 20° C. in this height.

C. (Isothermal Conditions. When the temperature remains the same with change of altitude the thermal condition is known as *isothermal.* Continued heating in lower levels of isothermal air may result in changes of *0.18° C.* to *0.36° C.* per 100 meters. Such thermal conditions are known as *weak lapse rates.*

D. Dry Adiabatic Lapse Rate. When the lapse rate is equal to the dry adiabatic rate (1° C. per 100 meters) it is known as

the *adiabatic lapse rate.* Superheating near the ground often causes the lapse rates in the lower layers to surpass the normal lapse rate. Lapse rates between .56° C. per 100 meters and .99° C. per 100 meters are known as *strong lapse rates.* When the rate equals 1° C. per 100 meters it is the adiabatic lapse rate.



a. Normal Lapse Rate

b. Lapse Rate Types

Fig. 20

E. Superadiabatic Lapse Rates. During the summer, in the afternoon, continued heating may cause the lapse rate in the lower layers to exceed the adiabatic lapse rate. Lapse rates greater than 1° C. per 100 meters are superadiabatic.

F. Auto-convective Lapse Rate. In certain special cases it is believed that the lapse rate may become so strong that rising air cools rapidly enough to maintain a constant density even though pressure decrease with altitude causes the air to expand. When the lapse rate of *3.42° C. per 100 meters* is reached simultaneous overturning results in such phenomena as dust devils.

G. Cloud Effects on Lapse Rates: In the daytime an overcast sky will prevent the lapse rates from becoming as strong as under clear conditions. The clouds act as a blanket to prevent either supercooling or superheating of the earth's surface. Within the main cloud mass itself lapse rates go to neither extremes of inversion nor the superadiabatic. Under ordinary conditions the lapse rates in the clouds are near to the average or normal lapse rate of .55° C./100 meters.

VIII. STABILITY OF THE ATMOSPHERE

In the previous paragraphs it has been shown that the air in the troposphere exhibits changes in temperature with changes in altitude. It has also been demonstrated that rising air cools at a definite rate (1° C. per 100 meters) until saturation occurs, then at a lesser rate, the value of which varies with the amount of water vapor being condensed. If a particle of air that is being forced upward remains cooler than the surrounding air at all times it will have a tendency to sink due to its own density level upon the removal of the lifting force. (*Note:* The density of an air particle is dependent upon its temperature and pressure. If the pressure is the same a particle of air at a higher temperature will have less density than a particle of air at a lower temperature.) Obviously, then, the stability of an air mass is dependent upon its lapse rate. If the temperature within an air mass falls quickly with altitude then the temperature of a rising particle might be higher than the surrounding air after it has risen. In that case it would continue to rise because of its own buoyancy and the air would be unstable. In stable air a displaced particle of air will tend to return to its original level. (Fig. 21)

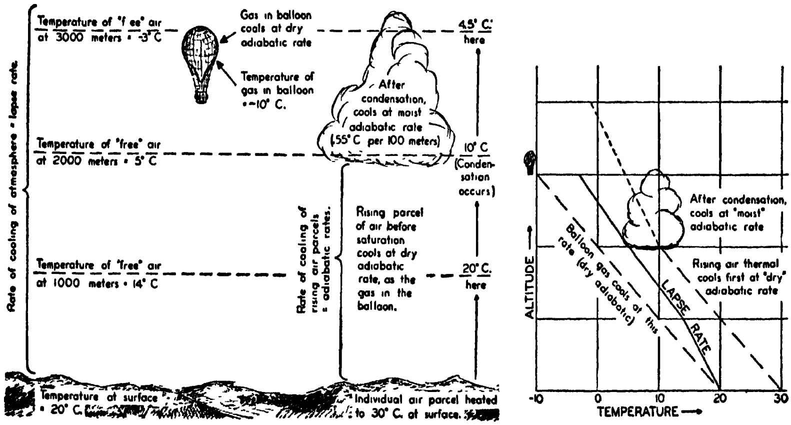


Fig. 21. Comparison of lapse rates and adiabatic rates.

A. Stable. When the lapse rate is less than either the dry or moist adiabats, the atmospheric temperature is always higher than that of a rising air parcel, which in rising cools at a more rapid rate, hence, this condition represents stability. Isothermal, or negative, lapse rates (inversions) represent very stable conditions since the rising air becomes relatively colder and denser while the atmosphere remains the same temperature and density or becomes warmer and relatively less dense. (Fig. 22)

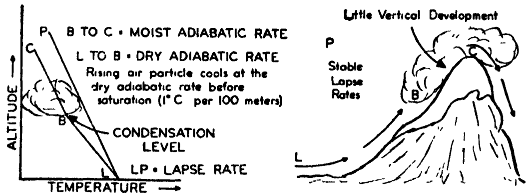


Fig. 22. Absolute stability.

In this diagram it will be noted that if the lapse rate had been greater the rising air might have become unstable after condensation. If the lapse rate had been superadiabatic, instability would have occurred before condensation. As illustrated, the rising air parcel is always colder than the surrounding air.

B. Unstable. When the lapse rate is greater than either the dry adiabatic rate or the moist adiabatic rate then the atmospheric temperature is always lower than the rising air parcels which can cool only at the adiabatic rates. Hence, this condition represents an unstable condition. (Fig. 23)

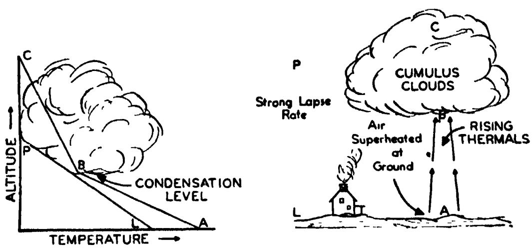


Fig. 23. Absolute instability.

If a rising particle of air is at all times warmer than the surrounding air mass it will always be lighter and will continue to rise. When this is the case the air is said to be absolutely unstable.

C. Conditionally Stable. When the lapse rate is between the dry adiabatic rate and the moist adiabatic rate, unsaturated rising air is stable until condensation takes place when the air may *become* unstable or become neutrally stable depending on the amount of moisture present. (Fig. 24)

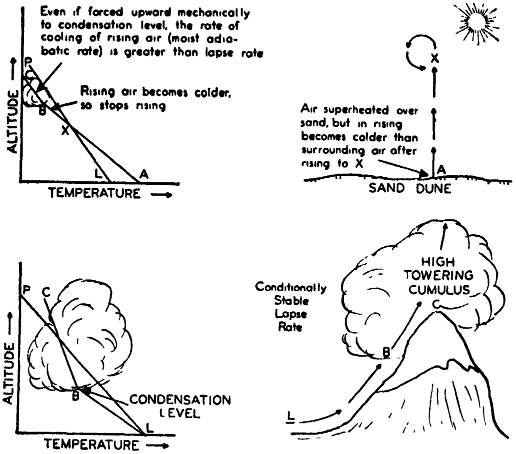


Fig. 24. Conditional stability.

If a rising particle of air originally colder than the surrounding air mass becomes warmer than this air mass it is said to be conditionally stable. Conversely, this condition is also illustrated by a rising air particle originally warmer than the surrounding air that becomes colder than this air mass upon rising.

D. Neutrally Stable. When the lapse rate is equal to the dry adiabatic rate the atmosphere's temperature drops at the same rate as rising air parcels; hence, it is neutrally stable to dry air. When the lapse rate is equal to the moist adiabat of the rising air the atmosphere is stable to rising dry air until condensation takes place, upon which it cools at a neutral rate. (Fig. 25)

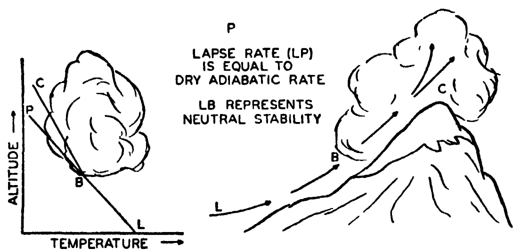


Fig. 25. Neutral stability.

When a rising particle of air cools at a rate equal to the adiabatic rate the air is neutrally stable. Under these conditions a particle of air will tend to remain at the level to which it is displaced. In this example the rising air becomes unstable after condensation (from B to C).

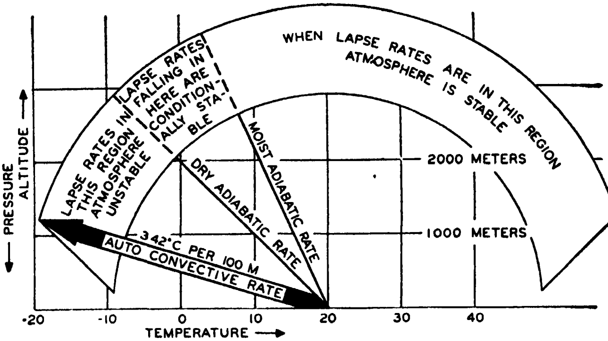


Fig. 26. Relation of lapse rates to stability.

TEST QUESTIONS ON THERMAL RELATIONSHIPS

1. The temperature at which all molecular motion ceases is (boiling point, solar constant, Réaumur zero, Absolute zero). 1. ________

2. The amount of heat necessary to raise one gram of water from 15° to 16° C. is the (kilogram calorie, gram calorie, B.t.u., degree). 2. ________

3. The average thermal energy of a mass is its (heat content, temperature, heat index). 3. ________

4. The amount of heat necessary to raise the temperature of one gram of a substance one degree centigrade is the (kilogram calorie, B.t.u., specific density, specific heat). 4. ________

5. — 18° C. is equal to the following Fahrenheit value (— 0.4° F., + 46° F., + 22° F., — 4° F.) 5. ________

6. 45° F. is equal to the following Centigrade value (23.4° C., 7.22° C., — 7° C., 10° C.). 6. ________

7. One hundred degrees' divisions on the Centigrade scale are equal to (100, 212, 459.4, 180) on the Absolute scale. 7. ________

8. To change Centigrade to Absolute the Centigrade value is added algebraically to (273, 459.4, 180, 212). 8. ________

9. To change Fahrenheit to the Absolute Fahrenheit the Fahrenheit value is added algebraically to (— 459.4, — 273, 273, 459.4). 9. ________

10. When heat is transferred through molecular contact the process is (absorption, advection, conduction, radiation, convection). 10. ________

11. When heat is transferred by currents set up in fluids the process is (absorption, advection, conduction, radiation, convection). 11. ________

12. When heat is transferred through space without the necessity of intervening matter the process is (absorption, advection, conduction, radiation, convection). 12. ________

13. When radiant energy from the sun is transformed into other forms of energy (absorption, advection, conduction, radiation, convection) has taken place. 13. ____________

14. The speed of electromagnetic energy is (300,000 m.p.s., 186,000 m.p.s., 300,000 m p.s., 1080 f.p.s.). 14. ____________

15. The Angstrom is equal to (10,000 microns, $\frac{1}{1,000,000}$ micron, $\frac{1}{10,000}$ micron, 100,000 microns). 15. ____________

16. The wave lengths of visible light are included between the wave lengths (.0132μ to .38μ, .38μ to .78μ, .78μ to 10μ, 10μ to 250μ). 16. ____________

17. The wave length of the infrared band is (.0132μ to .38μ, .38μ to .78μ, .78μ to 10μ, 10μ to 25μ). 17. ____________

18. The wave length of the ultraviolet band is (.0132μ to .38μ, .38μ to .78μ, .78μ to 10μ, 10μ to 250μ). 18. ____________

19. The shortest wave lengths of visible light are those of the (blue, red, green, indigo, orange, violet, yellow). 19. ____________

20. The (ultraviolet, infrared, visible light, radio) waves are most chemically stimulating. 20. ____________

21. The limits of solar energy are (.3μ to 2μ, .2μ to 3μ, .38μ to .78μ, .0132μ to 5μ). 21. ____________

22. The amount of insolation received at the top of the earth's atmosphere and measured in calories per minute per square centimeter is the (greenhouse effect, solar constant, selective absorption, ionizing layer). 22. ____________

23. The earth is (nearer, farther, same distance) (to or from) the sun in January than in July. 23. ____________

24. The fact that the earth eventually loses as much energy as it receives is called (insolation, greenhouse effect, heat balance, selective absorption). 24. ____________

25. The "variables" absorb about (43%, 5%, 40%, 7%, 12%) of the incident insolation. 25. ____________

26. About (80%, 5%, 40%, 7%, 12%) of the total incident insolation finally reaches the earth's surface. 26. ____________

27. Since water vapor is more permeable to short-wave radiation than long-wave the resulting phenomenon is known as (insolation, greenhouse effect, heat balance, solar constant). 27. ____________

28. Snow-covered ground and clear skies cause (inversions, superadiabatic rates, strong lapse rates, instability). 28. ____________

29. On clear days during the summer over the land in the afternoon (inversions, superadiabatic lapse rates, isothermal conditions) will be found. 29. ____________

30. Rising parcels of unsaturated air cool at the rate of (.55° C. per 100 meters, .18° C. per 100 meters,. 7° C. per 100 meters, 1° C. per 100 meters). 30. ____________

31. Rising saturated air parcels cool at the rate of (.55° C. per 100 meters, .18° C. per 100 meters, .7° C. per 100 meters, 1° C. per 100 meters). 31. ____________

32. The temperature at the surface is 20° C., at the 1000 meters' altitude the temperature is 16° C. This is a (stable, unstable, neutrally stable) lapse rate. 32. ____________

33. At sea level the temperature is 21° C., at 1000 meters the temperature is 10° C. This is a (weak, strong, normal, adiabatic, superadiabatic) lapse rate. 33. ____________

34. When the temperature remains the same with change of altitude the condition is (inversion, normal, superadiabatic, isothermal, adiabatic). 34. ____________

35. The auto-convective lapse rate is (3.42° C. per 100 meters, 1° C. per 100 meters, 2.73° C. per 100 meters, 3.65° C. per 100 meters). 35. ____________

36. Lapse rates in the air under a cloud layer become (stronger, weaker, remain the same). 36. ____________

37. If a rising particle of air is at all times cooler than the surrounding air a (stable, unstable, neutrally stable, conditionally stable) condition is represented. 37. ____________

38. If a rising parcel of air is at all altitudes warmer than the surrounding air the stability condition is (stable, unstable, neutrally stable, conditionally stable). 38. ____________

39. If the rising parcel becomes warmer than the surrounding air due to the liberation of its latent heat of condensation the stability condition is (stable, unstable, neutrally stable, conditionally stable). 39. ____________

40. If the lapse rate is equal to the rate of cooling of the rising air parcel the stability condition is (stable, unstable, neutrally stable, conditionally stable). 40. Neutral

CHAPTER IV

HUMIDITY, TEMPERATURE AND PRESSURE RELATIONSHIPS

I. VAPORIZATION

When liquids are transformed into the gaseous state the process is called *vaporization* and the product is a *vapor*. The name vapor is used because gases near the point of liquefaction deviate so far from the laws of Boyle and Charles that it is desirable to distinguish this state by a special name.

A. Evaporation. When the vaporization process takes place only at the free surface of a liquid it is called *evaporation*. Evaporation takes place at the surface of a liquid when molecules break away and assume the gaseous condition. This process takes place at all temperatures between the freezing points and boiling points of liquids. The most rapidly moving molecules vaporize first, leaving the remainder of the liquid with a lower energy content. Hence, evaporation is a *cooling process*.

B. Ebullition (Boiling). When sufficient heat is applied to a liquid, vaporization takes place not only at the surface but throughout the liquid. At the boiling point the vapor pressure of the liquid is equal to the atmospheric pressure.

C. Sublimation. Heat generally converts solids into liquids. However, certain substances such as camphor, "dry ice," iodine and musk are changed directly from the solid to the gaseous state. This process is called *sublimation*. Meteorologically, water vapor in the atmosphere is said to sublime when it changes directly from the vapor state to the solid state (ice crystals in cirrus clouds) without passing through the liquid condition.

D. Laws of Evaporation. The amount and rate of evaporation is important to many meteorological processes. The rate of evaporation is influenced by the following considerations:

1. The rate of evaporation increases with an increase of temperature.
2. The rate of evaporation increases as the surface area of the liquid increases.
3. The rate of evaporation varies with the liquid.
4. The rate of evaporation is increased with a reduction of pressure.
5. The rate of evaporation increases as the relative humidity is reduced.

X 6. The rate of evaporation increases with the rate of change of the air in contact with the liquid.

II. HEATS OF VAPORIZATION, CONDENSATION AND FUSION

When a substance undergoes a change of state, as from solid to liquid or liquid to gas, an energy exchange is required. Heat must be added to change a solid to a liquid or a liquid to a gas. Since energy cannot be destroyed, this energy is released when the changes, vapor to liquid and liquid to solid, are effected. (Fig. 27)

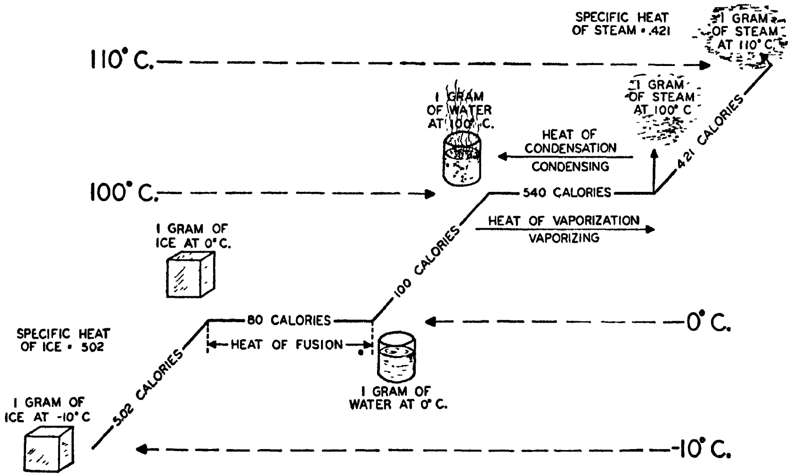


Fig. 27. Thermal history of one gram of ice.

A. Heat of Fusion. The number of calories necessary to change one gram of a substance from the solid to liquid state is known as the heat of fusion of the substance. 79.6 calories (roughly 80) are required to change one gram of ice at 0° C. to one gram of water at 0° C. The melting points and heat of fusion of some common substances are given in the following brief table.

	Melting Point	*Heat of Fusion*
Aluminum	657° C.	77 calories
Silver	960° C.	21 "
Mercury	— 39° C.	3 "
Ammonia	— 75° C.	108 "

B. Heat of Vaporization. The number of calories necessary to evaporate one gram of a liquid at constant temperature is known as the heat of vaporization of the liquid. At 100° C. and standard pressure about 539 calories are required to change one gram of water to one gram of steam at the same temperature. At

0° C. about 595 calories are needed to vaporize one gram of water. The heat of vaporization of some of the more common substances is given in the following table.

Substance	*Boiling Point*	*Heat of Vaporization*
Ammonia	— 38.5° C.	341 calories
Hydrogen	— 253.0° C.	108 "
Alcohol (ethyl)	78.3° C.	208 "
Mercury	356.7° C.	68 "

C. Heat of Condensation. Since heat is required to vaporize a liquid (heat of vaporization) a like quantity of heat is liberated upon condensation. Hence, when water vapor condenses heat is liberated. This liberated energy is known as heat of condensation. Evaporation produces cooling. Condensation causes heating.

III. HUMIDITY

The amount of moisture present in the air at any given time, temperature and pressure is very important to the meteorologist. Humidity is expressed in a number of different ways. The most common and important of these humidity relationships are included in the following discussion.

A. Capacity. The amount of moisture that can be contained in a given volume of air is known as *capacity.*

B. Absolute Humidity. The amount of moisture present in a unit volume of air expressed as grams per cubic meter is known as the *absolute humidity.* Absolute humidity may also be expressed as grains per cubic foot.

C. Relative Humidity. The ratio of the amount of moisture which the air does contain to what it could contain if saturated is known as the *relative humidity.* This value is expressed as a percentage.

1. *Example:* A given volume of air is found to contain 4.58 grams of water vapor per cubic meter at 0° C. The capacity at this temperature is 4.83 grams per cubic meter.

$$\frac{4.58}{4.83} \times 100 = 95\% \text{ relative humidity at } 0° \text{ C.}$$

If the air is heated to 20° C. it is found that the capacity increases to 17 grams per cubic meter at 20° C.

$$\frac{4.58}{17} = 26\% \text{ relative humidity at } 20° \text{ C.}$$

2. From the above example it is noticeable that when the water vapor content remains constant increasing the temperature decreases the relative humidity.

3. The average water vapor in the air is 1.2% by volume.

The maximum water vapor content is 4% by volume. The water vapor content replaces the nitrogen in the air to 77.08% and the oxygen to 20.75%.

D. Dew Point.

1. The dew point is the temperature to which unsaturated air must be cooled in order to reach the state of saturation. When this point is reached and exceeded any excess of water vapor will condense.
2. Warm air can contain more moisture than cold air. Air that is near the saturation point in a warm room will soon become saturated if chilled. Any excess moisture will condense and be forced out of the air. Hence, rising warm air will reach a certain altitude in rising where the dew point and the temperature will be the same. At this altitude clouds will first appear. It is apparent that the altitude at which clouds will appear will depend upon the rate of cooling of the rising air and its water vapor content. In a homogeneous air mass the dew-point temperature decreases at the rate of .2° C. per hundred meters. Hence, if at the surface the dew point were 10° C. and the temperature 20° C. condensation would not occur at 1000 meters because at that altitude the dew-point temperature would have decreased to 8° C. Since the dry adiabatic rate is 1° C. per 100 meters and the dew-point drop is .2° C., the lapse rate effective for convective cloud formation must then be .8° C. per 100 meters.

$$h = (T - T_s)\,\frac{100}{.8}$$

h = height of convective clouds in meters.
T = air temperature at surface.
T_s = dew-point temperature at surface.
Substituting in this formula:

$$h = (20 - 10)\,\frac{100}{.8} = 1250 \text{ meters.}$$

(height of formation of convective clouds).

IV. THE PSEUDO-ADIABATIC CHART

Many different types of energy diagrams have been used for the interpretation of upper-air soundings. Notable among these have been the Hertz-Neuhoff diagram, the emagram and aerogram of Refsdal, and the tephigram of Shaw. The common object of all these energy charts is to furnish a diagram upon which an aerological sounding may be plotted so that the path of any chosen particle of air may be traced as it ascends or descends through the surrounding medium. In this manner it becomes possible to determine whether mechanical

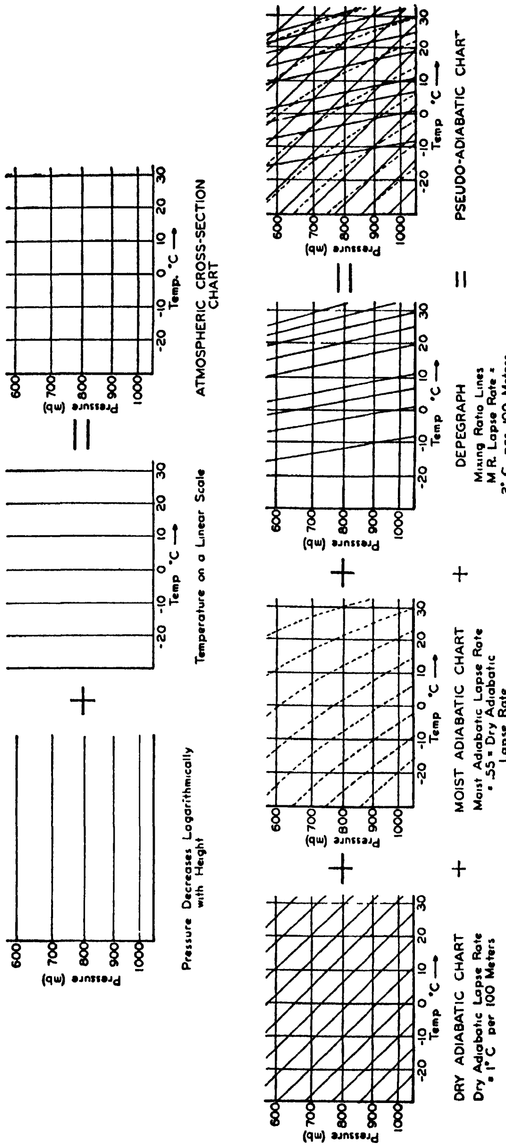


Fig. 28. Co-ordinates of the pseudo-adiabatic chart.

energy must be furnished to force the particle to rise. On such diagrams a necessary assumption is made that only one particle will rise through a stationary environment. Since such an assumption is artificial and does not fully or truly represent actual conditions in the atmosphere the successful interpretation of aerological data by use of energy diagrams is largely dependent upon a correct choice of a representative particle.

A. Co-ordinates of the Chart. The energy chart now in most common practical use throughout the United States is the pseudo-adiabatic chart. On the pseudo-adiabatic chart the abscissas are temperatures in degrees Centigrade, the ordinates are the 0.288 powers of the pressure in millibars. These values are represented on the chart by yellow lines drawn at right angles to each other. Sloping straight lines in yellow are used to represent dry adiabats. Moist adiabats are shown as slightly curving, broken red lines. Sloping, solid red lines are curves of constant saturation mixing ratio. These lines give the water-vapor content, in grams per kilogram of dry air, required for saturation at the indicated temperatures and pressures. (Fig. 28)

B. Plotting of Information on the Pseudo-adiabatic Chart. The temperature curve as obtained from upper-air soundings is drawn as a full line with mixing ratio values written in to its right. In addition a heavy dashed line is drawn on the chart with the

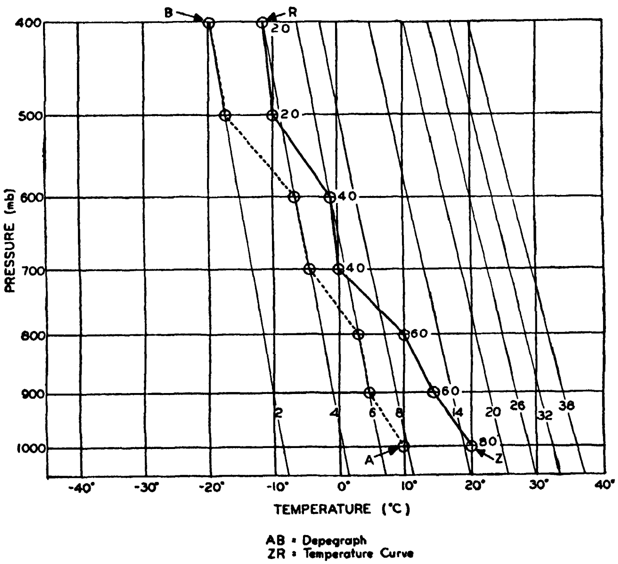


Fig. 29. Method of plotting information on the pseudo-adiabatic chart.

determining points being the mixing ratio values. This curve, the *depegraph,* serves to show at a glance the humidity conditions of the atmosphere in a manner similar to the way that the temperature curve indicates the thermal condition. The relative humidities are usually written beside the points of the depegraph. (Fig. 29)

C. Dew Point. Dew-point temperature may be found by merely tracing along the same pressure line (isobarically) as that of the point until the mixing ratio line for the value indicated is reached. For example, if the pressure at the point was 990 mb, the temperature 20° C. and the mixing ratio value 9 grams per kilogram, the dew-point temperature would be 12° C. (Fig. 30)

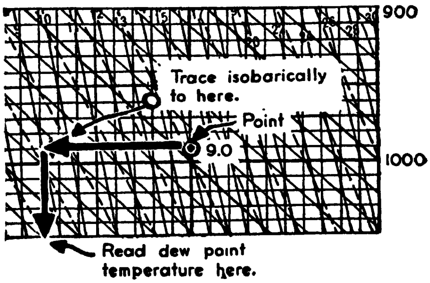


Fig. 30. Finding the dew-point temperature.

D. Lifting Condensation Level (LCL). To determine the level and temperature at which a parcel of air will become saturated if lifted mechanically, trace from the point up or parallel to the nearest dry adiabat until the mixing ratio line indicating saturation is intersected. For example, if the pressure temperature and mixing ratio at the point were as above in paragraph C the LCL would be at 10.5°C. and 885 mb. If a parcel of surface air were lifted to this point condensation would occur. (Fig. 31)

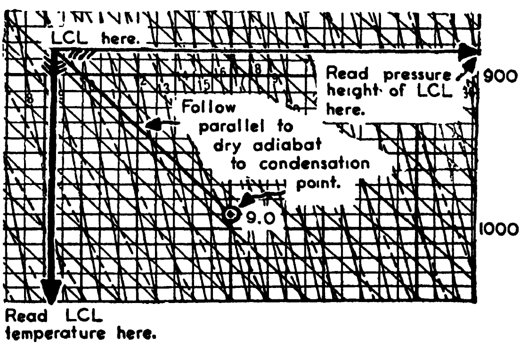


Fig. 31. Finding the LCL.

E. Convective Condensation Level (CCL). When air is heated it will rise. Because it is heated, however, such heated air will have to rise to a higher level before condensation will occur than it would if it were merely lifted mechanically in the first place. To find the level at which condensation will occur, when the air rises due to surface heating, follow the temperature curve up to the point at which it intersects the mixing ratio line indicating saturation. (Fig. 32)

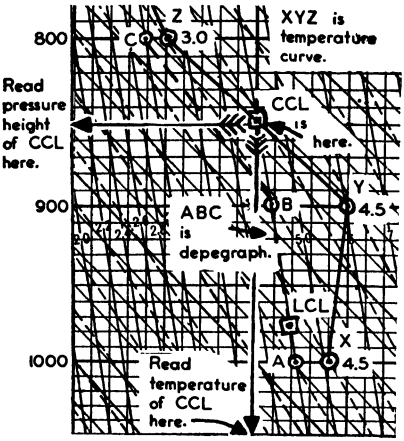


Fig. 32. Finding the CCL.

F. Temperature Necessary for Convection. An estimate of the temperature necessary for convection can be made by finding the CCL and then tracing down or parallel to the nearest dry adiabat to the surface. Once this temperature is reached thermal convection will take place freely and but little further surface heating can be expected since the heat will be distributed through the lower layers by convection. If the lapse rates are weak through a considerable depth of the lower atmosphere intense surface heating will be necessary to bring about free convection. Under the prevailing conditions of the time such intense surface heating might be highly improbable. This fact must be allowed for in using the above method for estimating maximum temperatures. In forecasting maximum temperatures for the surface the forecaster should be familiar with the locality for which he is forecasting. (Fig. 35)

G. Maximum Temperature. A similar method in common practice is to take for the maximum temperature of the day the surface temperature found by tracing from the top of the ground inversion or stable surface lapse rate down a dry adiabat to the sur-

face. The physical reasoning behind this procedure is that the surface inversion will preclude any thermal convection until it is removed by surface heating. Further heating will be inhibited beyond the removal of the ground inversion since most of the excess heat will be carried upward by convection and the temperature at the surface will remain at a fairly constant maximum. (Fig. 33)

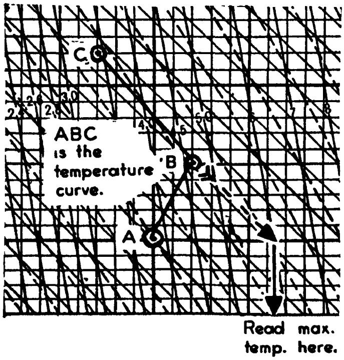


Fig. 33. Forecasting the maximum temperature.

H. Positive and Negative Areas. Positive and negative areas are plotted on the pseudo-adiabatic chart to show at a glance the stability conditions of the prevailing air mass. The parcel used to plot these areas must be chosen carefully. In choosing the mixing ratio value of the parcel which is to rise through the surrounding air mass it is common practice to select the mean value of the observed mixing ratio values through the lowest layers up to the condensation level. In other cases the humidity selected may be the mean humidity up to the top of any ground inversion or stable layer having relatively high humidity. (Fig. 34)

1. For thermal convection positive and negative areas may be plotted by choosing a surface particle and first finding its LCL. When the LCL is found trace up the mixing ratio line until the temperature curve is intersected and from that point (the CCL) follow a moist adiabat to the top of the chart. Areas enclosed by these lines lying to the left of the temperature curve are shaded in blue and represent negative energy areas. Areas enclosed by the lines described above but lying to the right of the temperature curve are shaded in red and represent positive energy areas. If the method just described is used to plot positive and negative energy areas the negative energy found at the surface levels is not strictly comparable area for area with the energy

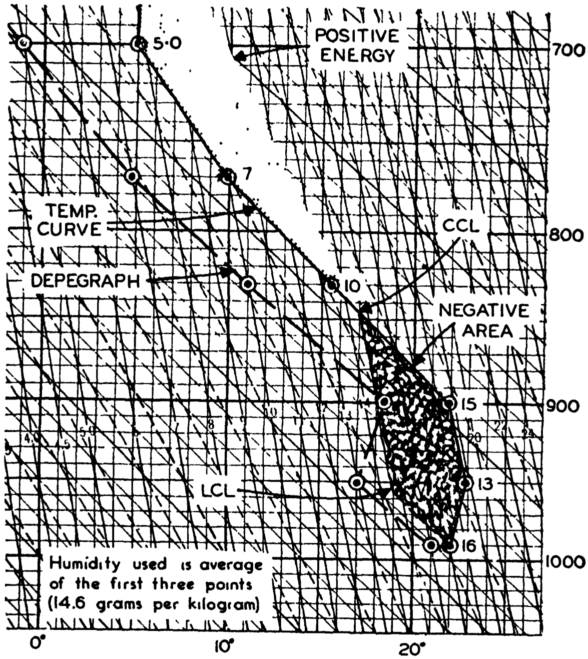


Fig. 34. A method for plotting energy areas for thermal lifting.

areas found aloft. However, if this method is used consistently the analyst soon learns to recognize the comparative values of the positive and negative areas even though these areas have different real values. When negative areas can no longer be plotted in the surface layers by this method then, by necessity, the lapse rate necessary to produce convection has been reached by surface heating. An alternative method now much in favor for plotting negative areas in the surface layers is shown in Fig. 35. The negative energy as plotted by this method has the advantage of being strictly comparable area for area with positive and negative areas found aloft. To plot negative areas at the surface by this alternative method the CCL is found first by tracing along the temperature curve until the saturation mixing ratio line is intersected. The saturation mixing ratio to be used is selected in the manner previously described. After finding the CCL the next operation is to trace parallel to a dry adiabat back to the surface. The area to the right of the temperature curve bounded on the left by the line drawn parallel to a dry adiabat from the CCL to the surface is shaded in blue

to represent the negative energy to be neutralized before convection can take place. Actually this negative surface area also shows the amount of heating required to cancel the effect of the stable surface layers and permit free convection from the surface (temperature necessary to produce convection). Air parcels must be lifted mechanically through negative energy areas; in positive areas these particles rise freely. Hence, large positive areas indicate instability with free convection while large negative areas represent stability. Since thunderstorms are associated with instability, air masses showing large positive areas, when either of the above procedures are carried out on the chart, are indicative of possible thunderstorms. (Fig. 35)

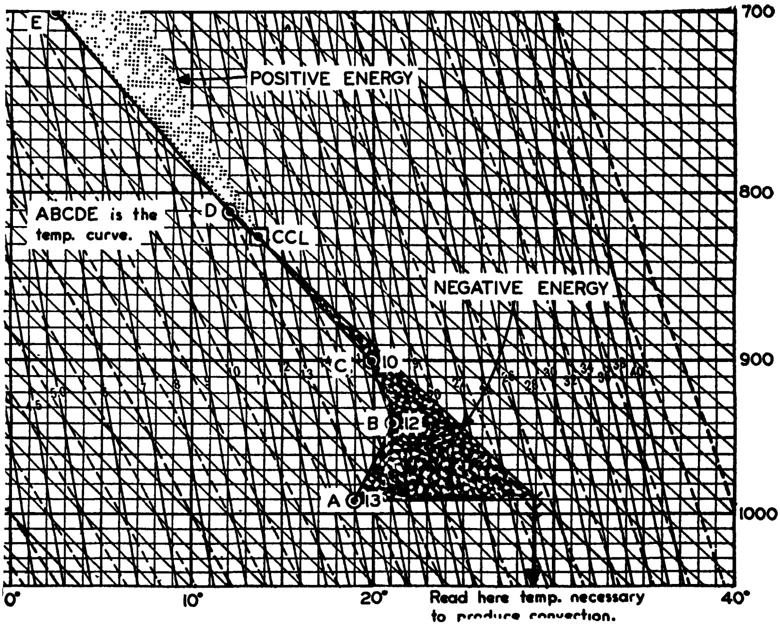


Fig. 35. An alternative method for plotting negative energy in the surface layers.

2. For mechanical convection positive and negative energy areas are plotted by selecting a surface particle and first finding its LCL. The moist adiabat is followed from the LCL to the top of the chart. Negative and positive energy areas lie in the same relative positions to the temperature curve as plotted by the method illustrated in Fig. 34. Energy areas are plotted for mechanical convection in forecasting

the possibility of thunderstorms associated with frontal or orographic lifting. When air is lifted along a frontal surface or over mountain barriers it will cool at the dry adiabatic rate until saturation. If the lapse rates in the air mass through which the air parcel is being mechanically lifted are stable in the lower layers and unstable or conditionally stable aloft, sufficient lifting beyond the LCL may result in the parcel becoming warmer than the surrounding air mass. As a result free convection will occur and convective type weather will result if the air can be lifted mechanically until the above condition is realized. The point at which the cooling rate of the rising parcel intersects the prevailing lapse rate may be designated as the mechanical convective level (MCL). (Fig. 36)

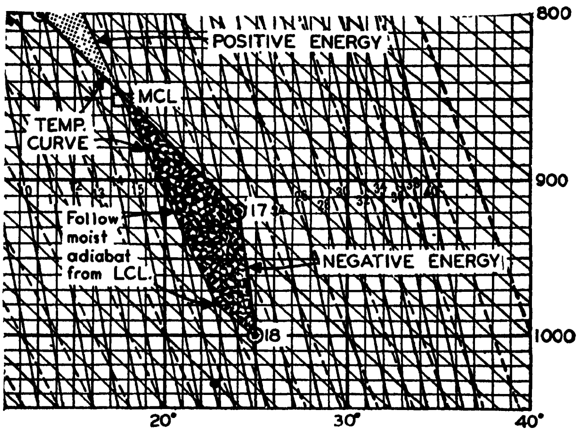


Fig. 36. Plotting energy areas for mechanical lifting.

I. Recognition of Fronts and Cloud Layers.

1. The presence of frontal surfaces is indicated by upper air inversions and by an increase in moisture content. The position of the surface front may be roughly estimated by allowing a slope of one-mile altitude per 50 miles horizontal displacement in the case of cold fronts and one mile to 150 miles for warm fronts. Thus, if the inversion occurs at an altitude of one mile on the chart and the front is a cold front, then the surface front must be 50 miles away, or if a warm front, 150 miles distant.

2. The radiometeorograph will indicate a relative humidity of, or near, 100% while passing through layers of clouds. Hence, cloud layers are indicated when the depegraph co-

incides with or closely parallels the temperature curve. The probable height of convective clouds may be estimated by examining the height of the positive areas as plotted on the pseudo-adiabatic chart. The top of the positive area aloft represents the point of maximum upward acceleration of the rising air parcel. Due to inertia, the rising air will usually continue upward until it has risen half of the vertical distance of the previous positive area beyond the point where it tends toward stability. Since the rising air is forming the convective clouds as it rises beyond the CCL or MCL the height of these clouds may be estimated in the manner described.

V. CONSERVATIVE THERMAL PROPERTIES

Ordinary properties of the air, like those of temperature and humidity, are variable. Due to adiabatic cooling and heating the particular temperature of any mass of air depends to a great degree upon the altitude at which it is found. The meteorologist must find properties of the air which are not so variable. As a result the so-called conservative properties have been derived. The theoretical reasoning involved in determining some of these conservative properties is presented, in outline, in the following paragraphs. Since the conservative properties may be recognized and determined by the use of the pseudo-adiabatic chart these methods are also given.

A. Although no physical property of the atmosphere can be strictly conservative, those physical properties which do not change quickly or frequently with the changing dynamical, kinematical and physical states of the air are called *conservative properties.* Such properties are useful in identifying air masses since they are not constantly changing.

B. Isothermal conditions are those where the heat content varies but the temperature remains constant. Isentropic, or adiabatic, are those conditions where the temperature may vary but the heat content remains constant. Many atmospheric changes are close to being isentropic. This is true because the portions of the atmosphere being considered are generally large enough so that changes within them are but little affected by their surroundings. Heat may be gained or lost by radiation or through turbulence.

C. Potential Temperature

1. For many meteorological purposes it is often desirable to compare the temperature of the air at different elevations and thus at different pressures. Since the temperature of the air is directly proportional to its pressure, if the temperature of air at various elevations is to be compared, all tem-

perature readings must be reduced to a common elevation. When this is accomplished adiabatically the resulting temperature at the 1000-mb level is called the ***potential temperature.***

2. Equation for potential temperature:

$$\theta = \frac{T}{\left(\frac{p_1}{P}\right)^k} \qquad K = \left(\frac{R}{m\,d\,C_p}\right)$$

T = Absolute temperature.
p_1 = pressure in millibars.
P = standard pressure.
k = constant involving the gas constant R.
md = molecular weight of dry air.
C_p = specific heat of dry air at constant pressure.

In the lower levels of the atmosphere, the adiabatic change in temperature with altitude amounts to 1° C./100 meters. If no heat is gained or lost an air particle, in being lowered from the 1500-meter level to the 500-meter level, will be heated 10 degrees Centigrade. If condensation does not occur, the air will be cooled a similar amount by rising the same distance. The potential temperature is conservative only when no condensation takes place. The rate of change of temperature in saturated air varies with the water vapor content. With a gain in altitude the air is unable to contain as much water, hence, at higher altitudes the lapse rate for saturated air approaches more closely that for dry air. Potential temperature is wholly conservative in regard to pressure changes if no condensation takes place.

D. Equivalent Potential Temperature. While the potential temperature is conservative insofar as pressure is concerned, it varies when condensation occurs. The equivalent potential temperature (θ_e) is obtained by lifting a particle of air to infinity (zero pressure) adiabatically, thus removing all its moisture and adding this heat energy derived from the latent heat of condensation of the water. (Upon condensation water vapor liberates about 580 calories per gram. This is known as latent heat of condensation.) The parcel is then lowered at the dry adiabatic rate to the 1000-mb level. This property is conservative to both pressure and condensation changes.

$$\theta_e = \theta_d e^{\frac{Lw}{C_p T}}$$

e = base of Naperian logarithms.
L = latent heat of condensation.

w = water vapor content in grams of water per gram of dry air.
C_p = specific heat of dry air at constant pressure.

E. Equivalent Temperature. The equivalent temperature is found in the same manner as is the equivalent potential except that the particle is returned to its original level rather than to the 1000-mb level. Hence, equivalent temperature is conservative for condensation processes but not for pressure changes.

F. Virtual Temperature. Moist air has a lower density than dry air. At any given pressure, the density is lowered by increasing the temperature. For certain practical purposes a fictitious increase in temperature can be made in just the right amount to account for the lower density caused by the presence of the water vapor. The temperature thus arrived at is known as the *virtual temperature*. The virtual temperature rarely exceeds the actual temperature by more than 3.5° C.

Equation of state.

$$pv = \frac{R}{m} T \qquad \text{or } p = \delta \frac{R}{m} T$$

p = pressure in dynes per cubic centimeter.
v = specific volume (number of cc occupied by 1 gram of gas) $v = 1/\delta$ where δ = density.
T = Absolute temperature.
m = gram molecular weight (28.99 for dry air and 18 for water vapor).
R = constant (universal gas constant).

Using the above units this last factor is the same for all gases and equals 8.315×10^7 ergs per degree centigrade per mol.

1 foot pound = 13,560,000 ergs.
mol = molecular weight in grams.

Thus the molecular weight of carbon dioxide is derived as follows:

Atomic weight of carbon = 12.
Atomic weight of oxygen = 16.

Since there are two atoms of oxygen for each atom of carbon dioxide, one mol of carbon dioxide would weigh 40 grams and would occupy 22.4 liters at standard conditions.

$T = t\ (1 + 0.6q)$
q = number of grams of water vapor per kilogram of humid air (specific humidity).

The equation of state then becomes:

$$P = \delta \frac{R}{md} T$$

$P =$ total pressure.
$\delta =$ density.
$md =$ molecular weight of "dry air."

VI. *CONSERVATIVE HUMIDITY PROPERTIES*

A. Specific Humidity. The mass of water vapor present in a unit mass of air is known as the specific humidity. The mass of the unit of air taken is considered still to be composed of the usual gas mixture plus the water vapor. The water vapor present is small compared to the mass of dry air with which it is associated.

B. Mixing Ratio. The mass of water vapor in a unit mass of dry air is called the mixing ratio. Since the mass of a unit of dry air differs but little from the mass of a unit of moist air, the mixing ratio and the specific humidity are nearly numerically equivalent. As unsaturated air particles ascend adiabatically, both the mass of the air and of the water vapor remain constant. Thus, both specific humidity and mixing ratio which depend on the ratio of these two quantities remain unchanged. It thus becomes obvious that these quantities are conservative. Such conservative properties, as given above, are useful in identifying air masses.

C. Formula for Specific Humidity.

$$g = 622\, e/p$$

$g =$ specific humidity.
$e =$ existent vapor pressure.
$p =$ total atmospheric pressure.

The units for e and p may be chosen arbitrarily, as they represent a ratio. The only requirement is that the unit chosen is the same for both values.

VII. *RELATIVE CONSERVATISM OF PHYSICAL PROPERTIES*

In the drawing (Fig. 37) it can be seen that as the air is forced to rise over the mountain certain properties change while others remain constant. The pressure changes from 1000 mb at 1, to 910 at 2, 800 at 3 and back to 1000 at 4. The relative humidity changes from 64% to 100% to 35%. The more conservative the property, the smaller will be the change observed. Thus, equivalent potential temperature remains constant at 296° A. at all points.

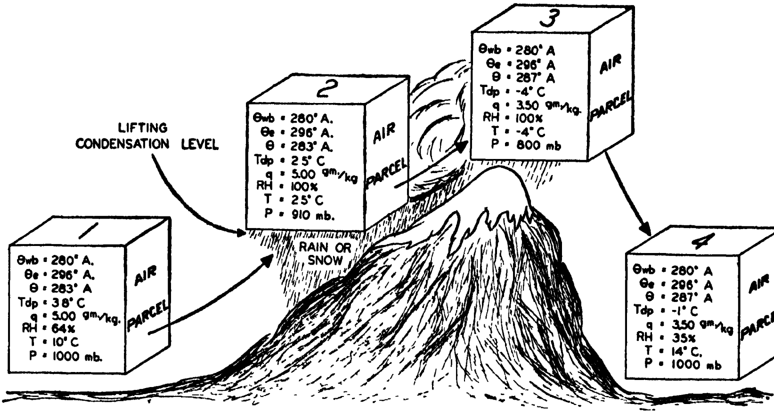


Fig 37. Comparison of conservative properties.

θ_{wb} = potential wet-bulb temperature. q = actual specific humidity.
θ_e = potential equivalent temperature. RH = relative humidity.
θ = potential temperature. T = temperature.
T_{dp} = temperature of dew point. P = pressure.

VIII. *EXAMPLES OF THE PRACTICAL USE OF THE PSEUDO-ADIABATIC CHART*

Given: Parcel of air at temperature = - 5° C. (Fig. 38)
Pressure = 900 mb.
Mixing ratio = 1.7 g/kg.

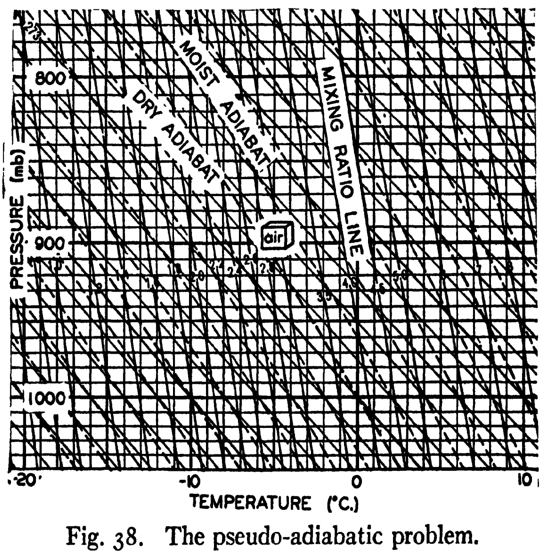


Fig. 38. The pseudo-adiabatic problem.

Find: (A) Saturation mixing ratio
(B) Relative humidity
(C) Dew point at ground
(D) Wet-bulb temperature
(E) Wet-bulb potential temperature
(F) Equivalent temperature
(G) Equivalent potential temperature
(H) Potential temperature
(I) Temperature at saturation
(J) Pressure at saturation

A. Saturation Mixing Ratio ($m. r_s$).

Read mixing ratio line which goes through 900 mb and −5° C. This is 2.93 g per kilogram.

B. Relative Humidity $= \dfrac{\text{actual mixing ratio}}{\text{saturation mixing ratio}}$

$$\text{R.H.} = \frac{1.7}{2.93} \times 100 = 58\%$$

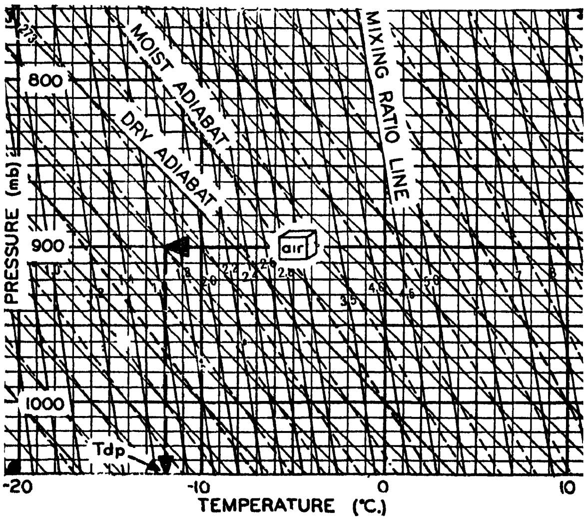


Fig. 39. The dew-point temperature.

C. Dew Point at Ground (T_{dp}) (Fig. 39).

Cool parcel isobarically (along the same pressure line) until it intersects the 1.7 g/kg mixing ratio line. Read the temperature.

D.P. = —12° C.

D. Wet-bulb Temperature (T_{wb}) (Fig. 40).
Trace up the dry adiabat to the saturation point, then down the moist adiabat to the original level. Read off the temperature. Wet-bulb temperature = — 7° C.

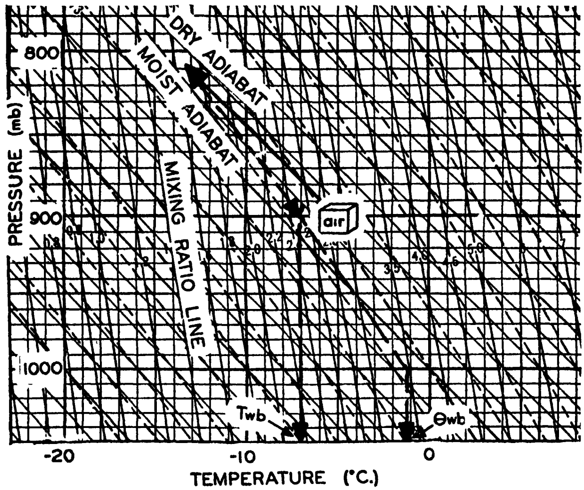


Fig. 40. Plotting the wet-bulb and potential wet-bulb temperatures.

E. Wet-bulb Potential Temperature (θ_{wb}) (Fig. 40).
Follow up the dry adiabat to saturation, then down the moist adiabat to the 1000-mb level. Read off the temperature. Wet-bulb potential temperature = — 1.1° C.

F. Equivalent Temperature (T_e) (Fig. 41)
Follow up the dry adiabat to saturation, then up the moist adiabat to the top of the chart (top of atmosphere). Using the nearest dry adiabat (or parallel to it) to the right of the moist adiabat originally traced, come down to the original level and read off the temperature. Equivalent temperature = — 1.8° C.

G. Equivalent Potential Temperature (θ_e) (Fig. 41).
Use the same procedure as in finding the equivalent temperature, except continue down the dry adiabat to the 1000-mb level and read off the temperature. Equivalent potential temperature = 7° C.

H. Potential Temperature (θ) (Fig. 42a).
Trace down the dry adiabat to the 1000-mb level. Read the temperature. Potential temperature = 3.6° C.

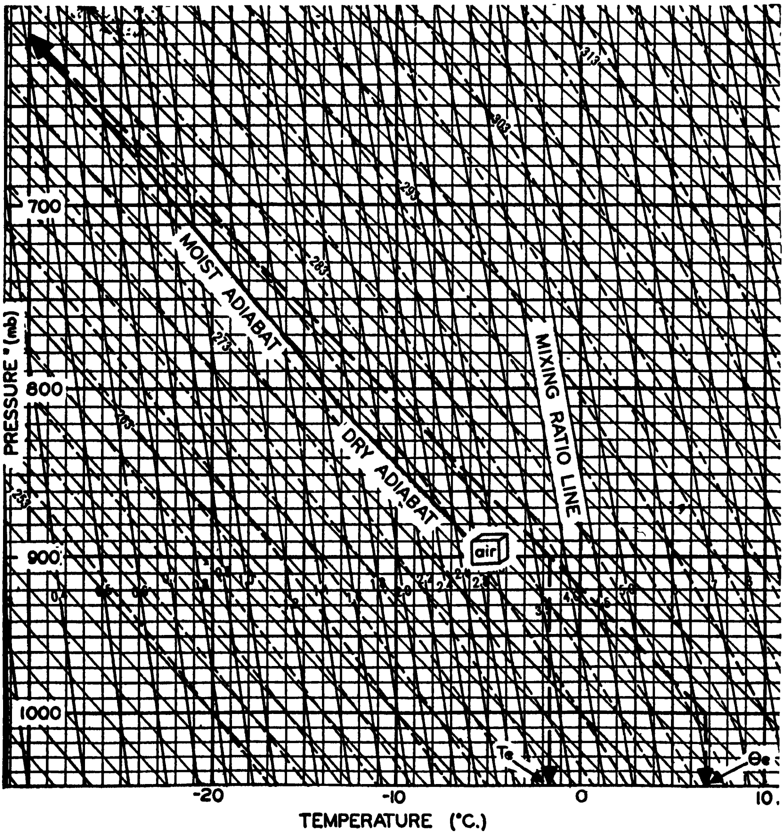


Fig. 41. Plotting the equivalent and the equivalent potential temperatures.

I. Temperature at Saturation (T_s) (Fig. 42b).
Follow the dry adiabat until it intersects the mixing ratio line which corresponds to the actual mixing ratio. Read off the temperature. $T_s = -13.1°$ C.

J. Pressure at Saturation (P_s).
Read off pressure at saturation point.
$P_s = 809$ mb.

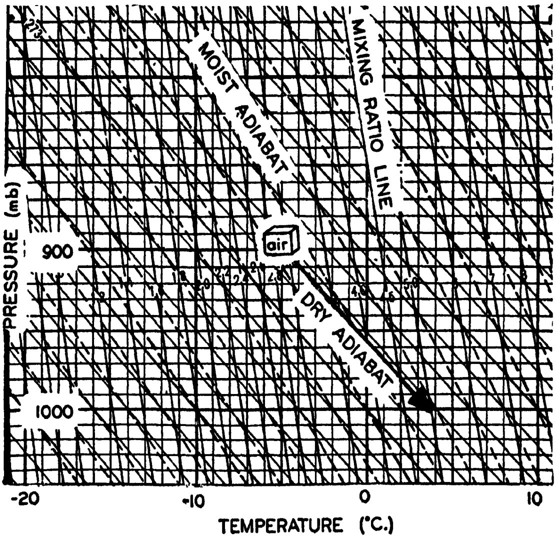


Fig. 42a. Plotting the potential temperature.

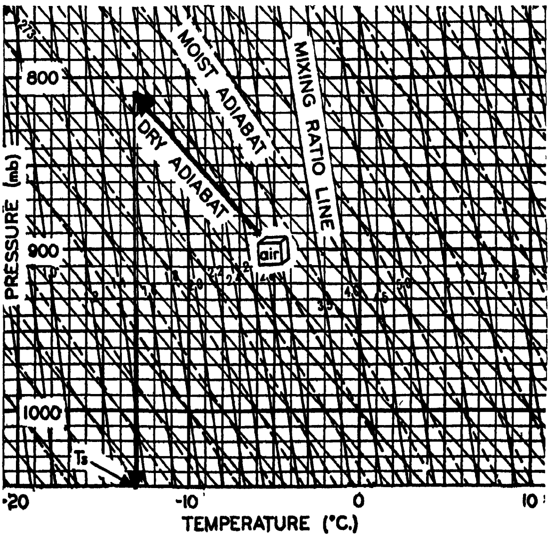


Fig. 42b. Finding the temperature at saturation.

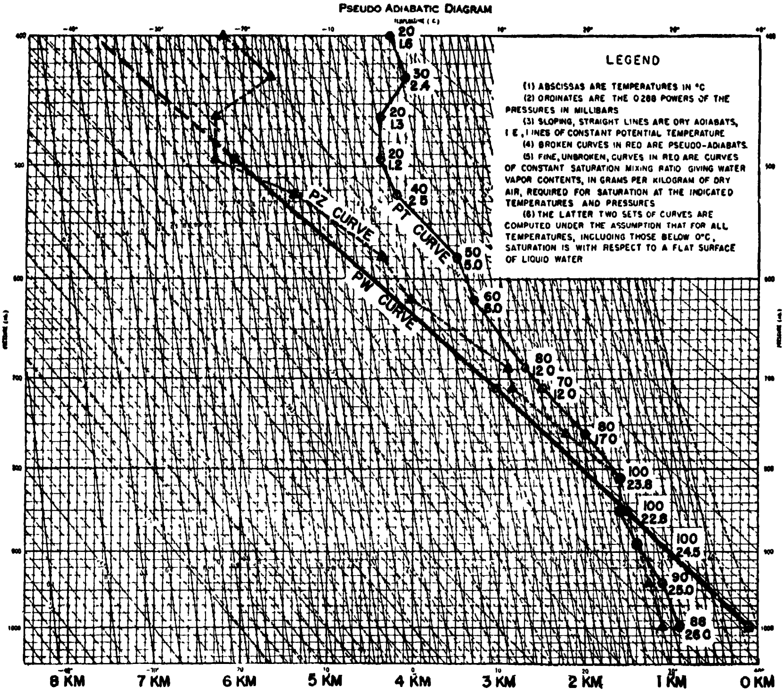


Fig. 42c. The completely plotted pseudo-adiabatic diagram. Coded as: 33405 99731 88694 40299 90260 49240 10240 60208 10157 87138 20076 80055 22524 95542 60542 30513 00532 10171 16050 34528 53870 72020 96050 12512 31324 516//

IX. THE COMPLETE PSEUDO-ADIABATIC CHART

In the preceding part of this chapter the various operations that must be accomplished on the pseudo-adiabatic chart have been presented in detail. In Fig. 42c the completely plotted chart is illustrated. Three curves are drawn on the completed chart, namely: the Pt (pressure-temperature) curve, the Pw (depegraph or humidity) curve and Pz (altitude) curve.

A. *Pt Curve.* The pressure-temperature curve is plotted by entering a point at the intersection of temperature abscissas with pressure ordinates. A circle is drawn around the plotted point and the relative humidity and mixing ratio are written to the right of the point as indicated in Fig. 42c.

B. *Pw Curve.* The pressure-dew-point curve or depegraph is plotted by connecting dew-point temperatures for each point by a dashed line. The method for finding dew-point temperatures is described on page 57. Each point is placed in a small triangle.

C. *Pz Curve.* The pressure-height curve is plotted on the basis of the information given in the third group of the code as to the 5000-ft., 10,000-ft. and 20,000-ft. levels and the altitude of the station above sea level. An altitude scale is superimposed over the temperature scale as illustrated in Fig. 42c. 40° C. is designated as sea level; each degree to the left is equal to 100 meters altitude. Thus, 39° C. is equal to 100 meters, 30° C. is equal to 1000 meters, etc. Since one meter is equal to approximately 3.28 ft., the 5000-ft. altitude level is equal to 1524 meters and is plotted isobarically opposite the point on the Pt curve given in the code as the 5000-ft. level. On the superimposed scale the 5000-ft. level is found along the 24.76° C. isotherm. $\frac{5000}{3.28} = 1524$ meters. Since 1° C. = 100 meters, $40 - 15.24 =$ 24.76° C. If the 24.76° C. isotherm is followed until isobarically opposite the point on the Pt curve designated as the 5000-ft. level, the second point on the Pz curve will be placed. Similarly the 10,000-ft. point is placed along the 9.52° C. isotherm opposite the Pt point designated in the code. Finally the 20,000-ft. point is plotted along the —20.96° C. isotherm opposite the Pt point designated in the code. Each point of the Pz curve is inscribed in a square and the points are connected with a straight line thus completing the Pz curve. By tracing isobarically from the Pt curve to the Pz curve and reading in terms of the superimposed altitude scale along the bottom of the chart, the altitude in meters of any point or phenomenon such as cloud levels can be determined. Thus, the base of the clouds at point B in Fig. 42c is at about 1010 meters above sea level and the top of the clouds at D is at about 1750 meters.

In Fig. 42c perform the operations listed below: (See page 228 for explanation of radiosonde code.)

1. Identify the lapse rate type between each pair of points. Thus the first type might be: Surface to Point A = isothermal. Print in space provided.
2. Calculate the relative humidity for each point.
3. Find the dew-point temperature for each point.

4. Find the equivalent temperature for each point.
5. Find the equivalent potential temperature for each point.
6. Find the potential temperature for each point.
7. By comparing the lapse rate from point to point with the dry and moist adiabatic rates list, in the space provided, the stability type represented.

TEST QUESTIONS ON HUMIDITY, TEMPERATURE AND PRESSURE RELATIONSHIPS

1. At temperatures between the freezing point and boiling point of a liquid, when the liquid changes to the gaseous state the process is (ebullition, evaporation, sublimation, boiling, vaporization). 1. ________

2. When the liquid changes to the gaseous state only at the free surface of the liquid the process is (ebullition, evaporation, sublimation, boiling, vaporization). 2. ________

3. At the (freezing point, boiling point, melting point, decomposition point) vapor pressure is equal to atmospheric pressure. 3. ________

4. When a gas changes directly to the solid state without passing through the liquid state the process is (ebullition, evaporation, sublimation, boiling, vaporization). 4. ________

5. The rate of evaporation is (decreased, increased, remains the same) with an increase of the atmospheric pressure. 5. ________

6. The number of calories necessary to effect the change from solid to liquid per gram of substance without causing a temperature change is the heat of (vaporization, condensation, fusion). 6. ________

7. The number of calories liberated per gram when a gas changes to a liquid is the heat of (vaporization, condensation, fusion). 7. ________

8. The number of calories necessary per gram to cause a liquid to change to a vapor without changing the temperature is the heat of (vaporization, condensation, fusion). 8. ________

9. The moist adiabatic rate is less than the dry adiabatic rate because energy is received from the heat of (vaporization, condensation, fusion). 9. ________

10. The amount of moisture that can be contained in a given volume is the (capacity, absolute humidity, dew point, relative humidity, specific humidity, mixing ratio). 10. ________

11. The number of grams of water vapor per kilogram of dry air is the (capacity, absolute humidity, dew point, relative humidity, specific humidity, mixing ratio). 11. ________

12. The ratio of the amount of moisture in a given volume to the saturation value is the (capacity, absolute humidity, dew point, relative humidity, specific humidity, mixing ratio). 12. ________

13. The number of grams of moisture per kilogram of moist air is the (capacity, absolute humidity, dew point, relative humidity, specific humidity, mixing ratio). 13. ________

14. The number of grams of water vapor per cubic meter is the (capacity, absolute humidity, dew point, relative humidity, specific humidity, mixing ratio). 14. __________

15. When the temperature of moist air is lowered the (capacity, absolute humidity, dew point, relative humidity, specific humidity, mixing ratio) will eventually be reached. 15. __________

16. The temperature of a homogeneous air mass is 18° C. and its dew point is 10° C. If convection takes place, clouds will begin to form at (640 meters, 1250 meters, 900 meters, 1000 meters, 875 meters). 16. __________

17. The dew-point temperature of a homogeneous air mass decreases (.2° C., .4° C., .1° C., .15° C., 2° C.) per hundred meters. 17. __________

18. The pseudo-adiabatic chart is (an upper air wind velocity chart, a humidity graph, a temperature graph, an energy diagram, a synoptic chart). 18. __________

19. Slightly curving, broken red lines on the pseudo-adiabatic chart are (dry adiabats, isobars, isotherms, mixing ratio lines, moist adiabats, depegraphs). 19. __________

20. Straight, solid, slanting yellow lines on the pseudo-adiabatic chart are (dry adiabats, isobars, isotherms, mixing ratio lines, moist adiabats, depegraphs). 20. __________

21. The depegraph is drawn on the pseudo-adiabatic chart as a (solid line, red line, solid black line, broken dashed line). 21. __________

22. When a parcel of air is moved up the dry adiabat until the saturation mixing ratio line is intercepted on the pseudo-adiabatic diagram, the point is the (dew point, wet-bulb temperature, LCL, potential temperature, equivalent potential temperature, CCL, equivalent temperature). 22. __________

23. Trace isobarically from the point on the temperature curve to the saturation mixing ratio line and the point found is the (dew point, wet-bulb temperature, LCL, potential temperature, equivalent potential temperature, CCL, equivalent temperature). 23. __________

24. Follow the temperature curve until it intersects the saturation mixing ratio line; the point is the (dew point, wet-bulb temperature, LCL, potential temperature, equivalent potential temperature, CCL, equivalent temperature). 24. __________

25. Find the LCL then follow the moist adiabat to the top of the chart, then back down the nearest dry adiabat to the original level, the point is (dew point, wet-bulb temperature, LCL, potential temperature, equivalent potential temperature, CCL, equivalent temperature). 25. __________

26. Follow the dry adiabat from the point on the temperature curve to the 1000-mb level, the point is the (dew point, wet-bulb temperature, LCL, potential temperature, equivalent potential temperature, CCL, equivalent temperature). 26. __________

27. Trace from the LCL along a moist adiabat to the top of the chart then back the nearest dry adiabat to the 1000-mb level, the point is (dew point, wet-bulb temperature, LCL, potential temperature, equivalent potential temperature, CCL, equivalent temperature). 27. __________

28. Find the LCL, then follow the moist adiabat to the original level,

the point is (dew point, wet-bulb temperature, LCL, potential temperature, equivalent potential temperature, CCL, equivalent temperature).

28. __________

29. Find the LCL, then follow the moist adiabat to the 1000-mb level, the point is (dew point, wet-bulb potential temperature, LCL, potential temperature, equivalent potential temperature, CCL, equivalent temperature).

29. __________

30. The area on a pseudo-adiabatic chart bounded by the temperature curve, a dry adiabat and the saturation mixing ratio line is (positive energy for thermal lifting, negative energy for thermal lifting, positive energy for mechanical lifting, negative energy for mechanical lifting).

30. __________

31. The area on the pseudo-adiabatic chart bounded by the temperature curve and a dry and a moist adiabat is (positive energy for thermal lifting, negative energy for thermal lifting, positive energy for mechanical lifting, negative energy for mechanical lifting).

31. __________

32. The temperature necessary to bring about thermal convection may be found by finding the CCL and then tracing down a (moist adiabat, dry adiabat, temperature line, mixing ratio line) to the surface.

32. __________

33. The maximum temperature may be estimated by tracing down a dry adiabat from the (LCL, top of inversion or stable surface layer, top of nearest surface unstable layer, isothermal layer) to the surface.

33. __________

34. When the depegraph approaches and touches or remains closely parallel to the temperature curve (instability, unsaturation, subsidence, clear skies, cloud layers) are indicated.

34. __________

35. An upper-air inversion with decreasing humidity usually indicates (frontal overrunning, cloud layers, precipitation, subsidence).

35. __________

36. An upper-air inversion with increasing humidity usually indicates (frontal overrunning, cloud layers, precipitation, subsidence).

36. __________

37. Underline the conservative properties in the following list. (Surface temperature, relative humidity, specific humidity, absolute humidity, capacity, potential temperature, equivalent temperature, equivalent potential temperature, mixing ratio.)

37. __________

38. The temperature of ten grams of ice is raised from $-10°$ C. to $110°$ C., with the ice changing to water and then to steam. (Specific heat of ice = .5 approx. Specific heat of water = 1. Specific heat of steam = .5 approx.) (819, 7290, 730, 5000, 1500) calories will be required to effect the change.

38. __________

39. Select the most conservative property of the following list. (Dew point, potential temperature, equivalent temperature, equivalent potential temperature.)

39. __________

40. The conservative property which is conservative for condensation processes but not for pressure changes is the (dew point, potential temperature, equivalent temperature, equivalent potential temperature).

40. __________

CHAPTER V

PRESSURE PHENOMENA AND WINDS

I. CAUSES OF THE WIND--THERMAL CAUSES AND GRAVITY EFFECTS

A. The primary cause of wind, as well as all other weather phenomena, can be traced to differences in the solar and terrestrial radiation which set up irregularities of temperature. These differences aid, in turn, in causing pressure differences. Gravity acting on the winds, which are set up to counteract these pressure differences, serves as the operative force.

B. All weather phenomena are fundamentally related to such atmospheric circulation. Large-scale air currents carry hot, moisture-laden air from the tropics into the temperate latitudes. Other large-scale air currents bring cold air from the poles to react with the warm tropical air, thus producing the large extra-tropical storms that bring most of our temperate zone weather. Small secondary circulations help bring about conditions modifying the general storm trend. Föhn winds melt away the snow. Sea breezes break the heat of a hot afternoon. Warm, moisture-laden air moves shoreward producing dense fogs. All of these conditions, and many more, are dependent on atmospheric circulation.)

II. PRESSURE

A. Historical. In past history, at various times, there was doubt as to whether the air was really matter. Air was thought to be a spiritual substance; hence, not akin to matter. At other times air was believed to be the essence of life. The reasoning was that living things breathe, dead things do not; hence, the difference between life and death is dependent upon partaking of this divine essence, the atmosphere. Such an attitude was, of course, unscientific and little progress was made in studying the air when erroneous ideas of this nature were universally held. When air was finally accepted as material in nature, then progress could be made in studying its properties.

1. Boyle's Law. Robert Boyle was one of the early scientists who worked with air as an experimental medium. He noticed that a variation in volume is produced in a gas by applying pressure. His law states: "If the temperature

remains constant the volume of a gas will vary inversely with the pressure applied." Thus, if a given volume of gas under one atmosphere's pressure is subjected to two atmospheres' pressure, its volume will be reduced to one half its original volume. This law has been expressed as: $P.V = P'.V'$

P = first pressure.
V = first volume.
P' = second pressure.
V' = second volume.

Example: First pressure of 1 cu. ft. of gas was 14.7 lb./sq. in. The pressure was then changed to 29.4 lb./sq. in. What was the final volume after the pressure change?

$$14.7 \cdot 1 = 29.4 \cdot V'$$
$$V' = .5 \text{ cu. ft.}$$

A corollary of this law states that the density of a gas varies directly with the pressure. This is expressed mathematically as: $\frac{D}{P} = \frac{D'}{P'}$

D = first density.
P = first pressure.
D' = second density.
P' = second pressure.

Example: A gas has the density of .0765 lb./cu. ft. at a pressure of 14.7 lb./sq. in. What will its density be at 29.4 lb./sq. in.?

$$\frac{.0765}{14.7} = \frac{D'}{29.4} \qquad D' = 0.153 \text{ lb./cu. ft.}$$

2. Charles' Law. Another early scientist working with gases noted that heating caused expansion and that cooling caused contraction. This law may be stated in the following manner: The volume of gas varies directly with the Absolute temperature. This is expressed mathematically as: $\frac{V}{T} = \frac{V'}{T'}$

V = first volume.
T = first Absolute temperature.
V' = second volume.
T' = second Absolute temperature.

Example: One cubic foot of air at a temperature of 0° C. is subjected to a temperature of 273° C. What is the final volume?

Note: The Absolute temperature equals 273 + the Centigrade.

$$\frac{1}{273 + 0} = \frac{V'}{273 + 273}$$

$V' = 2$ cu. ft.

3. Correction for both Temperature and Pressure. Boyle's and Charles' Laws can be combined to yield the following formula:

$$\frac{PV}{T} = \frac{P'V'}{T'}$$

$P =$ first pressure.
$V =$ first volume.
$T =$ first Absolute temperature.
$P' =$ second pressure etc., etc.

Example: Find the volume, at 20° C. and 740 mm pressure, of a 500-cc sample of air taken at 30° C. and 770 mm pressure.

$$\frac{770 \cdot 500}{273 + 30} = \frac{740\,V'}{273 + 20}$$

$V' = 503.1$ cc (new volume)

4. Pressure and Force Exerted by Wind. The pressure of a wind is proportional to the square of its velocity.

$$F = .005\,Av^2$$

$F =$ total force.
$.005 =$ constant (dependent upon pressure and temperature of the air).
$A =$ area in square feet.
$V =$ velocity in miles per hour.

A wind of 15 m.p.h. will exert about 1⅛ lb. pressure per square foot; at 30 m.p.h., 4½ lb. per square feet; and at 60 m.p.h., 18 lb. per square foot.

B. Material Nature of the Air. We are living at the bottom of a "sea of air." Our bodies sustain pressure because of the depth and density of our atmosphere. Since the air stays with the earth despite its rotation and great velocity through space, air must respond to the pull of gravity; hence, the conclusion that air is matter and has weight. A room full of air (10 ft. on a

side) weighs about 80 lb. In comparison one cubic foot of water weighs 62.4 lb.

C. The weight of air produces pressure. If a column of air, one inch on a side and as high as the atmosphere, was weighed, it would be found to weigh about 14.7 lb. So we conclude that at standard conditions (temperature = 0° C.) and at sea level the atmospheric pressure = 14.7 lb. per square inch.

In 1643, Torricelli, by using mercury instead of water, proved that it is the pressure of the atmosphere that sustains liquids in exhausted tubes. The first barometer was a medium-size glass tube about one yard long and closed at one end. The variations of the height of mercury in such a tube give indications of the variations in atmospheric pressure. Pressure decreases roughly at the rate of one inch per 1000-ft. gain in altitude. Temperature variations help to bring about noticeable pressure changes. There is a diurnal change in the temperature that brings about a consequent diurnal pressure change which is superimposed on the prevailing pressure field. The highest diurnal pressure occurs at 10 a.m., the lowest at about 4 p.m. Characteristic planetary pressure zones can also be traced to such thermal differences.

D. Cause of Pressure Variations. The atmosphere is not heated at all points with equal intensity. When air is heated the molecules of which it is composed are accelerated. They then tend to draw away from each other and the air expands. Since the molecules now occupy a greater volume, the density of the parcel of heated air has been decreased. As a result, the heated air will be buoyed upward by the surrounding denser air and will rise. Such rising air currents (thermals) tend to reduce the air pressure at a given locality, and the denser air flowing in to fill in the low-pressure areas thus gives rise to horizontal currents or winds. Hence, the conclusion that winds are primarily due to pressure differences in the atmosphere which owe their presence to irregularities in heating.

III. THE PRIMARY CIRCULATION OF THE ATMOSPHERE

Several modifications of the general scheme of the primary circulation, as presented here, are extant. Since all of these methods attempt to generalize and simplify a very complicated natural condition the system given is as true in its representation of the planetary air movements as is necessary for a general understanding. (Fig. 43a)

A. Doldrums. The greatest heating takes place at the equator. The air rises at the equator thus creating a zone of low pressure

of about 10° each side of the thermal equator known as the *doldrums.* (The thermal equator is an imaginary line passing through the center of the belt of high temperature where maximum insolation is received. At the time of the equinoxes the thermal equator and the geographical equator coincide.) As the air rises from the doldrums the resultant expansion due to reducing pressure aloft causes the air to cool and it very quickly reaches its dew point.) Inasmuch as equatorial air character-

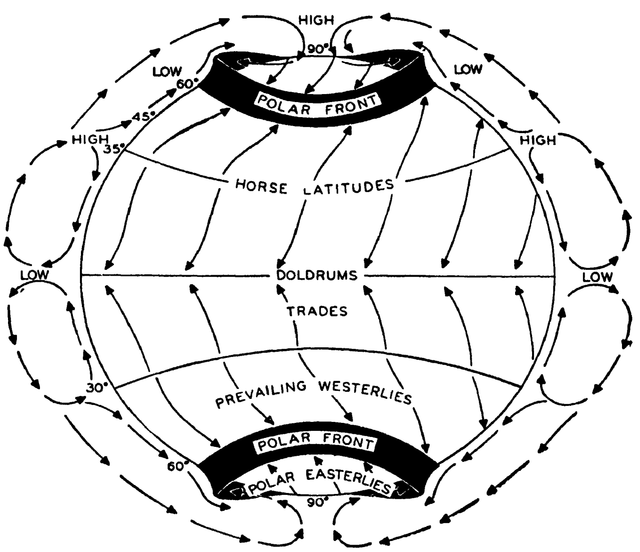


Fig. 43a. The general circulation.

istically has a high specific humidity the conditions are favorable for heavy rains daily in the central doldrums) The trade winds from northeast and southeast, because of both convergence and heating, rise above the surface as they near the equator. Beneath these converging winds aloft a belt of light variable winds and calms are found at the surface.) (In this hot, stagnant, moist air at the surface conditions are favorable for convection and heavy rainfall.) Because dry air is more dense than moist air, as the rising air precipitates its moisture its density is increased. In addition, expansional cooling contributes to the density increase of the rising air with the result that as it reaches the upper limits of the troposphere it ceases to rise. Since it is impossible for this risen air to sink immediately to the surface because of the converging surface winds it spirals poleward while it remains aloft. Traveling poleward aloft as antitrade winds

the air further cools by radiation to space. The rotation of the earth deviates these upper troposphere antitrades from their straight path into a spiral so that at latitudes 30° to 35° north and south a partial damming effect impedes the poleward flow. Subsidence, due to the increased density caused by cooling, and the damming effect combine to produce the high pressure belts known as the horse latitudes.

B. Horse Latitudes. Because of the cloud dissipating effects of heating by subsidence a belt of calms or light variable winds and fine, clear weather is found between the trade wind belt and the zone of prevailing westerlies. The belts are about 10° in width and are located about 35° N. and 30° S. of the thermal equator. Surface winds blow northward from these horse latitudes resulting in the westerlies and southward resulting in the trade winds. Due to the motion of the earth these northerly and southerly winds are made to veer (be deflected to the right of the path of motion) in the Northern Hemisphere and back (be deflected to left of path of motion) in the Southern Hemisphere, thus assuming their characteristic direction.

C. Polar Front. As shown in diagram (Fig. 43a), some of the upper winds continue on beyond the horse latitudes and proceed spirally poleward. In subsiding at that point they create a polar, high-pressure area. Easterly winds then blow out from the poles. At about 60° latitude these polar winds encounter the winds of the prevailing westerlies. Since the air in these polar winds is cold it does not rise over the westerlies. Instead, it is dammed up and, when a sufficient quantity of air collects, the entire reservoir spills over into more southern latitudes. It is this spilling over of the cold polar air into southern latitudes that is so important in creating our temperate zone weather. (Fig. 43b)

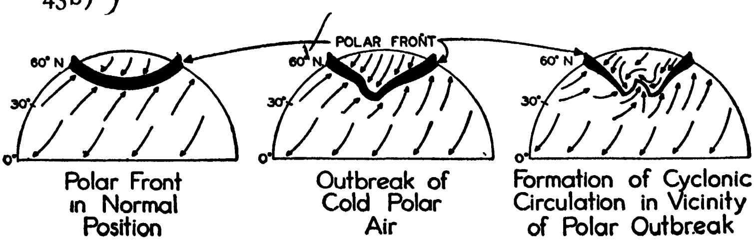


Fig. 43b. The ideal polar outbreak.

D. The Trade Winds. These winds blow southward from the horse latitudes. The rotation of the earth gives rise to a change in their motion. Instead of pursuing their course in a great circle

they are deviated to the right in the Northern Hemisphere and to the left in the Southern Hemisphere.

1. Coriolis Force. If the wind is moving with the velocity V the acceleration to the right is given by $d = 2\omega \sin\phi V$. ω is the angular velocity of the earth (one revolution per day or $2\pi/24$ radians per hour), and ϕ is the angle of latitude. $d =$ Coriolis force. (Fig. 44)

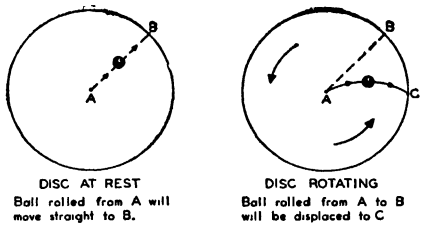


Fig. 44. Effect of the earth's rotation on wind direction.

2. Due to the deviating effect of the earth's rotation, the trade winds of the Northern Hemisphere are northeast trades and those of the Southern Hemisphere become southeast trades. At high altitudes some returning winds are noticeable. These are known as the *antitrades.*

E. The Prevailing Westerlies. From the high-pressure zone of the horse latitudes, winds blow in a poleward direction toward the low-pressure area near the polar front. These winds, due to the earth's rotation, veer to the right in the Northern Hemisphere and to the left in the Southern. Hence, they assume a westerly component from which they derive their names. In the Southern Hemisphere, where there is relatively more open ocean and the winds are not influenced by surface irregularities, the westerlies are of high velocity. Because of this fact a region around the southern tip of South America has been given the name of the Roaring Forties. The Forties refer to the approximate latitude.

F. The Centers of Action. The main modifications of this simple ideal circulation occur at the *centers of action.* In the northern Pacific, near the Aleutian Islands, the semipermanent Aleutian Low is found, while on the Atlantic side, the Icelandic Low reaches its maximum activity during the winter. In the general vicinity of the horse latitudes the Azores High is found in the Atlantic Ocean. In the Pacific Ocean the Pacific High lies off the coast of southern California during the summer while in the winter it moves inland over this region. In the winter, seasonal highs are found over northern Canada, the North American

High, and over Siberia, the Siberian High. These semipermanent centers impress their cyclonic or anticyclonic circulations on the general ideal circulation described previously. (Fig. 45)

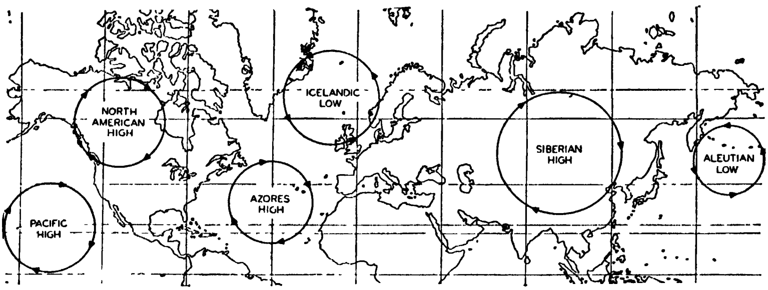


Fig. 45. Centers of action.

Northern Hemisphere, showing the winter highs as they occur over Canada and Siberia.

G. Factors Affecting the Primary Wind System. As has been demonstrated the primary wind system is a function of thermal differences inherent to our earth as a planetary body. Differences in heating give rise to differences in pressure which in turn set up wind systems. These winds are influenced in their direction over the earth's surface by:

1. Earth's rotation.
2. Centrifugal force.
3. Frictional and topographical effects.
4. The secondary circulation.

Wind increases in speed with height due to a freedom from frictional and topographical effects. Over the sea surface the wind is reduced to about two thirds of its speed in the free air. Over the land the speed at the surface may be reduced to one third of that of the free air.

H. Ferrel's Law. The effect of the earth's rotation on the wind has been stated in the form of a law. Thus, Ferrel's law states that: "When a mass of air starts to move over the earth's surface it is deflected to the right in the Northern Hemisphere and to the left in the Southern Hemisphere, and tends to move in a circle whose radius depends upon its velocity and its distance from the equator." The operation of this law is more effective over the sea than over the land where turbulence interferes.

I. Forces Acting on Moving Air. (Fig. 46)

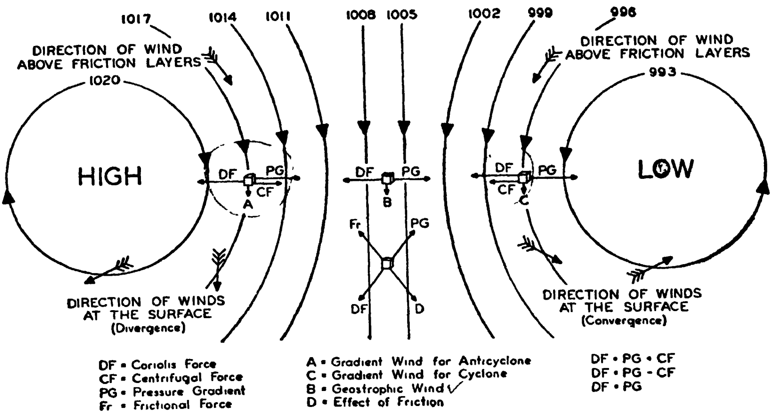


Fig. 46. Balance of forces.

1. Pressure Gradient. The air originally starts to move over the earth's surface because of pressure differences. The rate of change per unit distance in the horizontal direction is known as the *pressure gradient.* Strong winds blow when the pressure gradient is *steep;* when the pressure gradient is *flat* or *weak* the winds are light. The strength of the pressure gradient is indicated by the spacing of the isobars on the synoptic chart. *Isobars* are lines drawn on the chart to connect points of equal pressure. When the isobars are close together it indicates that the change of pressure in the horizontal direction is rapid and the pressure gradient is steep. When the isobars are widely spaced the converse is true and the winds are light. Once a body of air is set in motion, due to pressure differences in the horizontal direction, the air will continue to move until its original energy is dissipated by friction, orographic and mixing effects. (Newton's First Law of Motion: A body tends to remain at rest or continue in its original path of motion until acted upon by an outside force.)

2. Coriolis and Centrifugal Effects. After the air is set in motion by the original pressure gradient force, other forces start to act on the moving air. The Coriolis force, as previously described, tends to cause the wind to veer to the right of its path of motion in the Northern Hemisphere. As the air starts to assume a circular path, centrifugal force begins to act upon the moving particles. In a low-pressure area above the friction layer, gradient force just equals the combined effect of the Coriolis and centrifugal forces. In

a high-pressure area above the friction layer, gradient and centrifugal forces balance the Coriolis force. When these forces balance each other and the wind blows parallel to curved isobars the wind is known as the *gradient wind.* A wind blowing parallel to straight isobars is known as the *geostrophic wind.* At the equator where Coriolis force is not operative a wind comparable to the above is called *cyclostrophic.* These winds are all upper-air winds and are found above the friction layer (above 1500 to 2000 ft.).

Frictional Effects. While the above winds may be found in the upper air, the wind next to the surface tends to drift across the isobars. This effect is the result of the fact that of the several forces acting upon moving air only gradient force is independent of the velocity of the moving air. Coriolis and centrifugal forces are both increased by an increase in velocity. Friction slows the air speed near the surface. As a result the Coriolis and centrifugal effects are lessened and the air starts to flow at an angle across the isobars resulting in convergence at the surface in low-pressure areas and divergence at the surface in high-pressure areas.

IV. THE SECONDARY CIRCULATION OF THE ATMOSPHERE

In addition to the primary circulation of the atmosphere there are many variations set up in these general planetary winds due to various local effects. Such effects include thermal, topographical and pressure differences. The local variations in the primary circulation constitute what is known as the *secondary circulation.*

A. The Monsoon. The regions most favorable to the development of monsoons are in the middle latitudes. The term is applied to certain winds which blow with great persistence and regularity at definite seasons of the year. In fact, the word monsoon is derived from the Arabic word for "season." The word originally referred to the winds of the Arabian Sea, which blow for about six months from the southwest and six months from the northeast. The most characteristic monsoon is found in India and southern Asia. They also occur to a lesser extent in north Australia, parts of western, eastern, and southern Africa, and North and South America.

The Indian Monsoon. In the summer the land, since it has a low specific heat, will heat up more quickly and to higher temperatures than the sea. To increase this effect the thermal equator and surrounding zones move northward with the sun in the summer. Hence, the broad land areas of India heat rapidly and rising thermal currents are gener-

ated. This results in a low-pressure area being set up over the land. Then, relatively, the air over the Indian Ocean represents a high-pressure area. Winds start to blow from the high-pressure area to the low-pressure area. These winds are of maritime origin; hence, they are moisture-laden. Now a topographical effect of the continent of Asia becomes noticeable. The land of India rises steadily from the coast to the mountains of Tibet. The moisture-laden wind blowing landward is forced to rise. In rising the air begins to precipitate its water vapor. (Thus, with the summer monsoon in India, torrential seasonal rains occur.) The winter monsoon represents the reverse of these conditions. The air blowing seaward is cold and dry. Very little rain occurs during the winter months because of the dry winter monsoon. (Fig. 47) ✓

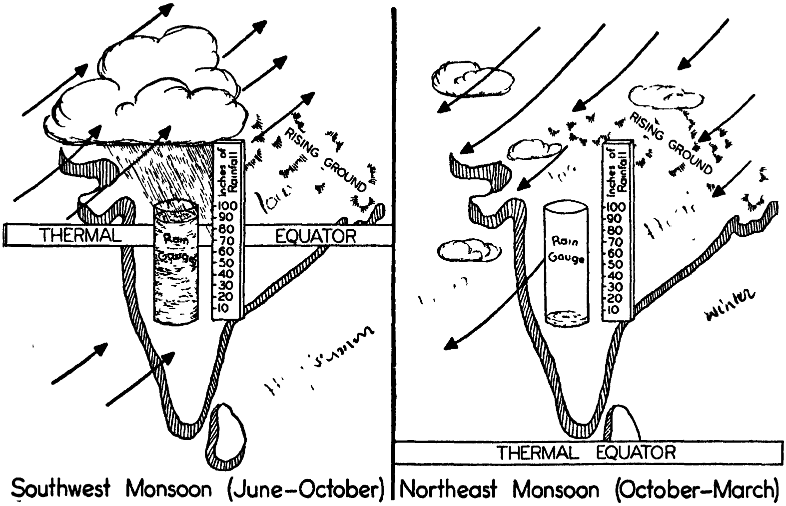
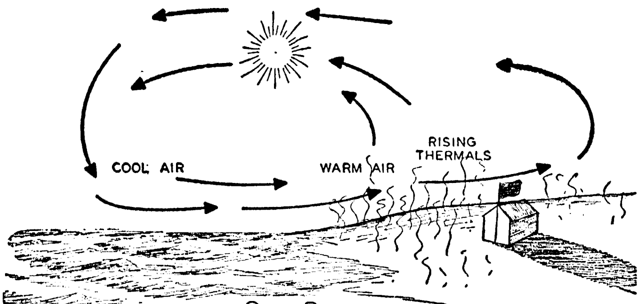


Fig. 47. The monsoons of India.

B. Land and Sea Breezes. These winds are caused by unequal heating and cooling of land and water areas as influenced by solar radiation during the day and radiation to space at night. This phenomenon produces a gradient of pressure near the coast. The general description of the origin of land and sea breezes is the same as that for the monsoon, with the difference that the change is diurnal (occurring daily) rather than seasonal. The nocturnal land breeze, the sea breeze's corollary, is usually less developed than the sea breeze. The depth of the current of the sea breeze

is shallow to start with but will increase to as much as 1800 to 2000 ft., at the time of maximum development. Sea breezes may extend to from 15 to 20 miles from the coast both inland and seaward. They usually originate about two miles seaward and blow about ten miles inland. The speed of the sea breeze rarely exceeds 12 m.p.h. On some occasions, however, it may reach speeds as great as 25 m.p.h. The sea breeze usually becomes noticeable between two and three o'clock in the afternoon. The exact time varies according to local conditions and the distance from the seashore. The onset of the sea breeze, when it takes place suddenly, may be accompanied by a noticeable squall, a sudden fall in temperature (as much as 6° C.), and an increase in humidity. The intensity of the sea breeze increases in lower latitudes. The sea breeze decreases toward evening. (Fig. 48)



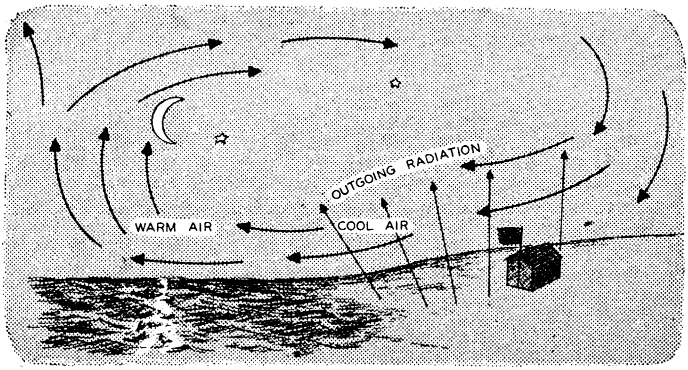


Fig. 48. Land and sea breezes.

Mountain and Valley Circulation. Air, in contact with the ground of the valley walls, is heated and cooled quickly by conduction, while air in the center of the valley can be cooled or

heated only by radiation or convection. During the day the air rises along the walls of narrow valleys producing updrafts. At night the circulation is reversed with downdrafts along the walls of the canyon. Such air currents are to be avoided by light planes and nonrigid airships, particularly in mountain passes. (Fig. 49)

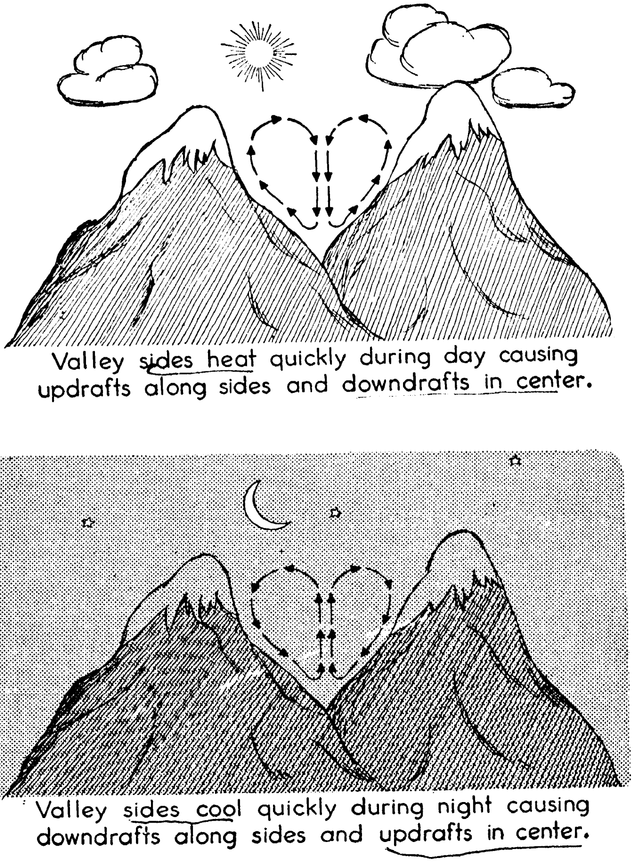


Fig. 49. Mountain and valley circulation.

D. Anabatic Winds. When the surface of the ground has an appreciable slope there is a tendency for surface winds to drift up or down the slope. This effect is due to convection. If the slope is heated by the sun the air in contact with it becomes warmer than the air at the same level which is not in contact. Hence, this heated air tends to ascend. Such ascending winds

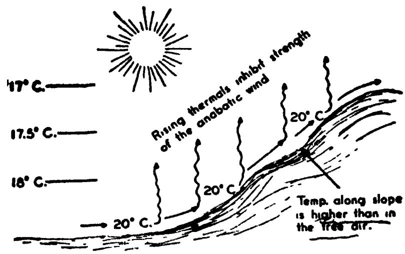


Fig. 50. Anabatic wind.

are called *anabatic winds.* (Fig. 50) Often they are masked by the effects of vertical convection. When anabatic winds are intensified by the funnel effect of a valley they are called *valley winds.* (Fig. 51)

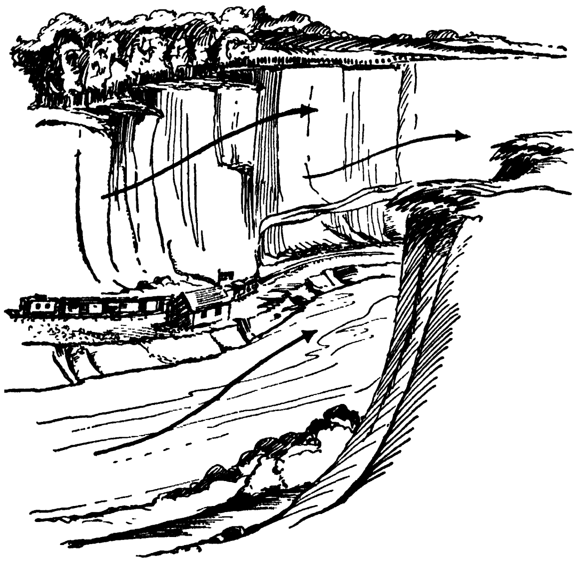


Fig. 51. Valley winds and the funnel effect.

E. Katabatic Winds. The reverse of the anabatic wind is the *katabatic wind,* which occurs characteristically at night. These winds occur when the ground on a slope is colder than the air at that height. Since no vertical thermal currents are found in cold air all of the air will flow downslope. The concentration of such cold air in low places often results in fog or mist collecting in shallow valleys (radiation fog). On high, snow-covered moun-

tains or glacier-covered country katabatic winds may occur during the day. The "Bora" of the Adriatic sometimes reaches speeds of 100 m.p.h. due to local effects, plus katabatism. Katabatic winds are also found in Greenland and the Black Sea. Katabatic winds are cold and often have a high relative humidity as the wind continues in contact with a cold surface and the consequent cooling renders the dynamical heating ineffective. (Fig 52)

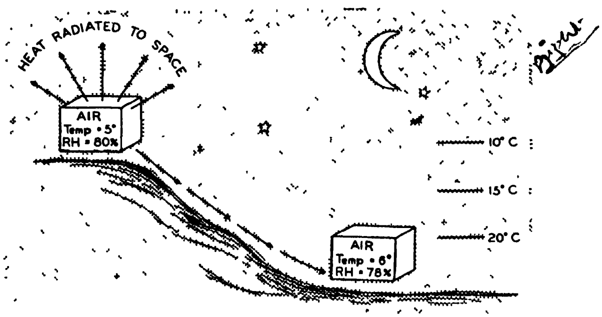


Fig. 52. A katabatic wind. Cold air, acted upon by gravity, flows downslope preserving its low temperature and high relative humidity.

F. The Föhn Wind (Chinook). Winds may be forced to rise mechanically over a mountain barrier. In this way adiabatic cooling takes place and orographic rain may result (rain caused by interference of rising land in the path of moisture-laden wind). The condensing water vapor yields its latent heat of condensation to the rising air so that when it descends on the lee side of the mountain barrier it regains its original temperature by adiabatic heating, plus the added temperature, as a result of the heat of condensation. Since the condensation has taken place largely on the windward side of the barrier, the descending wind then is both warm and dry. Such föhn winds cause rapid thaws if they occur in the winter or early spring. Föhn winds may be accompanied by lenticular clouds. Föhn winds may cause temperature rises of as great as 20° to 25° C. The weather in southern California is often markedly modified in the winter by a föhn wind known locally as the Santa Ana. (Fig. 53)

G. Highs and Lows. Traveling disturbances of great area originate along the polar front. These pressure systems carry with them their own wind systems. In the Northern Hemisphere winds blow out of (diverge) high-pressure areas in a clockwise direction. In lows, the winds converge and spiral toward the

low-pressure center in a counterclockwise direction in the Northern Hemisphere.)

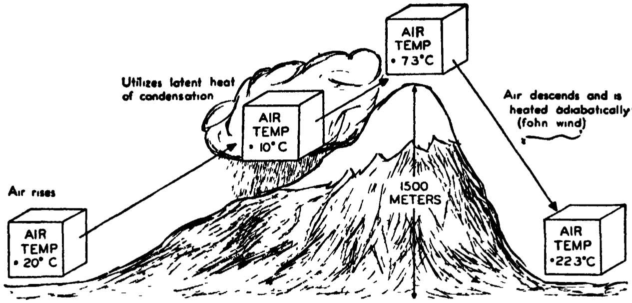


Fig. 53. The föhn effect.

V. *IRREGULAR VARIATIONS IN THE MEAN WIND*

A. Wind-shift Lines. In the part of the world where traveling pressure systems occur, the winds are variable. The passage of a front (line of separation between unlike air masses) brings about wind shifts. The front where this wind shift occurs is, then, also known as a *wind-shift line.*

B. Structure of the Wind (Gustiness and turbulence). Gustiness and turbulence in the mean wind is best indicated by a pressure-tube anemometer.

Gustiness Factor. To study the changing character of the mean wind a factor has been developed known as the *gustiness factor.* This factor is calculated on the basis of an arbitrary unit time such as one hour.

Gustiness factor = range between lulls and flurries in gusts/mean wind.

The gustiness factor is expressed as a percentage.

Example: Lowest wind = 15 m.p.h.
Highest wind = 45 m.p.h.
Mean wind = 30 m.p.h.

$$\text{Gustiness factor} = \frac{45 - 15}{30} \text{ times } 100 = 100\%.$$

C. Causes of Gustiness.

1. Mechanical Effects. Irregularities in the terrain will lead to mechanical effects and thus produce eddy currents which are carried along by the wind. Over open, level country or the sea such effects are minimized. Winds blowing offshore from the land are apt to be gusty.

2. Thermal Effects. Gustiness due to thermal effects is diurnal. Circumstances which cause little diurnal variation in the surface temperature will tend also to eliminate the variation due to turbulence. Thermal currents are usually more noticeable to aircraft than mechanical gustiness, due to the greater magnitude of the former. Thermal eddies may extend to a mile or more. Eddies of this magnitude may require more than two minutes to pass a given point. When this is true such eddies are classified as secondary disturbances or squalls. To aircraft the strongest gusts to be expected are more important than the mean wind, since they are more likely to produce structural strains and difficulties in landing or during the take-off.
3. Squalls. The essential difference between squalls and gusts lies in the time factor. Gusts are merely transient increases in the mean wind lasting for a period of a few seconds. The squall is an increase in the mean wind lasting usually for some minutes and then generally dying away. Squalls are never entirely due to mechanical factors. Other factors such as clouds, precipitation, and temperature variations affect squalls.
4. Diurnal Variations in the Wind. During the night turbulence is weak since uneven heating does not take place. Hence, the undisturbed wind is reached at a low altitude (500 to 600 ft.). In the daytime these lower layers lie well within the frictional layer and thus suffer loss in momentum and deviation in direction. Turbulence smooths out the differences between the free air and the surface layers. As a result, such differences are small in the daytime and great at night. For instance, on a clear night the surface winds may be only 3 to 5 m.p.h., while at 2000 ft. the wind may be 20 to 25 m.p.h. With the coming of day a veer in direction of as great as 15° to 20° also may result along with an increase in speed of the surface wind.

* D. Mechanical Deviations in the Wind due to Ground Contour.

1. Funnel Effect. Wind, in blowing against mountain barriers, tends to flatten out and go around them. If the barrier is broken by a pass or valley the air will be forced through with considerable velocity. Under such circumstances winds of 39 to 46 m.p.h. may be reached locally in a valley while the general wind is only 19 to 24 m.p.h. In such narrow valleys the wind is always from one end or the other and, hence, gives no reliable indication of the direction of the general wind. Such forcing of wind through mountain valleys is known as the *funnel effect*. (Fig. 51)

2. Vertical Motion of the Atmosphere. Irregular currents may occur near the ground or in cumulo-form clouds. Such currents are usually not dangerous but annoying to aviation. In conditions where the atmosphere becomes vertically unstable due to heating of the air near the ground or other causes, particularly when cumulus or cumulonimbus clouds develop, vertical currents may become very strong and reach to 30,000 ft. or more. Upward currents are indicated by the clouds and are found below and within them.
3. Local Currents due to Buildings and Ground Contour. When the air is unstable the whole air flow may be turbulent to considerable heights. If the lapse rate is less than the adiabatic rate, the undisturbed air flow is reasonably smooth. Wind tends to go around objects rather than over them. In front of an orographic obstacle the wind velocity is lowered in the lower layers. In some extended mountainous areas, as a result, the winds may have rather low velocities in valleys. A glider pilot knows from experience that comparatively low and extended slopes, such as sand dunes, are more favorable for soaring than individual, isolated mountains, although the latter might be much higher. When the change from level ground to ridge is abrupt, turbulence and eddies result. Steep grades and abrupt edges bring about eddies and turbulence. Due to inertia of the air particles and lee eddies, the highest point of a slope current is found behind the ridge summit. To the lee of steep hills small but intense downdrafts may be created by the lee eddy.

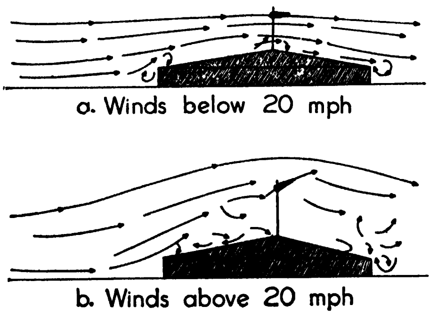


Fig. 54. Mechanical turbulence increases with increased wind velocity.

In Fig. 54, if the wind were blowing over the building in case (A) toward the field, an airplane taking off over the building would experience a downward bump and then an upward bump. Buildings

should be cleared by at least their own height if a take-off over them is unavoidable. In some cases bumps over a ground obstacle may reach to three or four times the height of the obstacle.

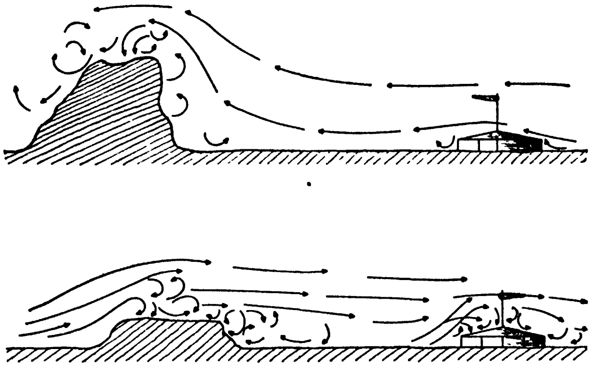


Fig. 55. Mechanical turbulence with slope and ridge currents.

The above cases represent conditions on a field adjacent to a change in elevation As shown, such currents can be dangerous to aircraft particularly if they are heavily loaded or underpowered.

TEST QUESTIONS ON PRESSURE PHENOMENA AND WINDS

1. One cubic foot of air at two atmospheres' pressure is subjected to five atmospheres' pressure. The new volume becomes (500 cu. in., 691 2 cu. in., .5 cu. ft., .3 cu. ft., 728.3 cu. in.). 1. ________

2. Two cubic feet of air at $-162°$ C. are heated to 60° C. The new volume becomes (1 cu. ft., 3 cu. ft , 4 cu. ft., 10 cu. ft., 6 cu. ft.). 2. ________

3. If the temperature remains constant the volume of a gas will vary inversely with the pressure applied. This is a statement of the law of (Charles, LaSalle, Dines, Boyle). 3. ________

4. A gas has a density of .08 lb. per cubic foot at 760-mm pressure. At 3 atmospheres' pressure if the temperature is unchanged the new density will be (.026 lb. per cubic foot, .4 lb. per cubic foot, .04 lb. per cubic foot, .24 lb. per cubic foot, .8 lb. per cubic foot). 4. ________

5. The total force exerted by a 20-mile wind on an area 2 ft. by 2 ft. is (4 lb., 8 lb., 16 lb., 2 lb., 6 lb.). 5. ________

6. The highest diurnal pressure occurs at (6 p.m., 1 p.m., 8 p.m., 4 a.m., 10 a.m., 7 a.m.). 6. ________

7. One atmosphere's pressure may be expressed as (underline all correct answers) (600 lb. per square foot, 2117 lb. per square foot, 10 lb. per square inch, 14.7 lb. per square inch, 1013.25 mm of mercury, 760 mb, 1013.25 mb, 34 ft. of water, 760 mm of mercury, 29.92 in. of mercury, 14.7 in. of mercury). 7. ________

8. When surface heating causes rising currents of air they are known as (adiabats, isotherms, thermals, isobars, katabatic currents).

8. ________

9. A belt of relative calm near the thermal equator is the (horse latitudes, trades, Pacific anticyclone, doldrums, mistrals).

9. ________

10. At the time of the summer solstice the thermal equator coincides with the (equator, Tropic of Cancer, horse latitudes, doldrums, Tropic of Capricorn, polar front). 10. ________

11. Winds are (westerly, easterly, northerly, southerly) at the poles.

11. ________

12. The latitude where polar winds meet the westerlies is known as the (horse latitudes, doldrums, Tropic of Capricorn, polar front, Tropic of Cancer). 12. ________

13. $d = 2\omega \sin \phi \; v$ is the ~~formula~~ expressing (Boyle's law, Charles' law, force exerted by moving air, Coriolis force, centrifugal force).

13. ________

14. A wind is named on the basis of (the direction from which it is blowing, the direction to which it is blowing, the direction perpendicular to its direction of travel). 14. ________

15. The trades are (east, west, north, south, southeast, northeast, northwest, southwest) winds in the Northern Hemisphere. 15. ________

16. The westerlies are really (east, west, north, south, southeast, northeast northwest, southwest) winds in the Northern Hemisphere.

16. ________

17. The antitrades are (east, west, north, south, southeast, northeast, northwest, southwest) winds in the Southern Hemisphere.

17. ________

18. List the permanent centers of action. ________

____
____
____
____

19. List the seasonal centers of action. ________

____
____
____
____

20. Over the sea surface the wind is reduced to (one third, two thirds, one half, four fifths) the speed of the free air. 20. ________

21. The law that states the effect of the earth's rotation on the wind is (Boyle's, Ferrel's, Buys Ballott's, Charles'). 21. ________

22. List the four effects that influence the direction of the wind. ________

1) pressure gradient
2) coriolis & centrifugal force
3) Frictional effect.
____

23. Which of the above is independent of frictional effects?

23. ________

24. Lines on the synoptic chart which connect points of equal pressure are (isotherms, fronts, isallobars, isobars, isopycnals). 24. ________

25. A wind that blows parallel to curved isobars is a (katabatic, föhn, anabatic, gradient, geostrophic, cyclostrophic) wind. 25. ________

26. A wind that blows parallel to straight isobars is a (katabatic, föhn, anabatic, gradient, geostrophic, cyclostrophic) wind. 26. ________

27. Friction causes the winds in a high-pressure area to (converge, ascend, descend, subside, diverge) at the surface. 27. ________

28. In India the summer monsoon blows (landward, seaward). 28. ________

29. Torrential rains are associated with the (summer, winter) Indian monsoon. 29. ________

30. The monsoon effect is increased by the northward displacement of the (equator, polar front, Tropic of Capricorn, thermal equator). 30. ________

31. Land- and sea-breezes are (seasonal, diurnal, monthly, semi-annual). 31. ________

32. Sea breezes extend to (5000, 10,000, 18,000, 1800) ft. altitude. 32. ________

33. When the sea breeze occurs the pressure over the land is relatively (higher than, the same as, lower than) that over the sea. 33. ________

34. The sea breeze may be expected at locations near the coast around (3 p.m., 6 p.m., 9 a.m., 12 m., 10 a.m.). 34. ________

35. In narrow canyons (downdrafts, updrafts) may be expected along the walls at night. 35. downdraft

36. Winds blowing upslope during the day are (geostrophic, anabatic, gradient, cyclostrophic, föhn, gradient) winds. 36. ________

37. The Bora is an example of a (geostrophic, anabatic, föhn, gradient, cyclostrophic, katabatic) wind. 37. ________

38. A warm dry wind blowing downslope is a (katabatic, geostrophic, cyclostrophic, anabatic, föhn, gradient) wind. 38. ________

39. Thermal gustiness (is greater, is less) than mechanical gustiness. 39. ________

40. The lowest winds at the surface are usually (at night, during the day). 40. ________

CHAPTER VI

AIR MASSES

I. THE NATURE OF AN AIR MASS

When air of substantially the same horizontal structure covers a large area it is called an air mass. An air mass has been defined as an extensive portion of the earth's atmosphere having approximate horizontal homogeneity. After air masses have acquired their characteristic properties they travel as an almost solid current. Air often stagnates over sections of the earth's surface where it acquires the thermal and moisture characteristics of the region over which it has stagnated. The depth to which an air mass will become modified by the characteristics of its source region depends upon the length of time that it remains there, and also on the relative temperatures of the air and the surface over which it lies. When air lies over continental polar areas it cools from below. As a result thermal currents do not develop and vertical mixing can take place only to a limited extent through turbulence. If the air mass stagnates for some time under such conditions, the inversions which originally developed, due to surface cooling, are deepened by gradual subsidence from aloft. Air masses originating under the above conditions are usually shallow. On the other hand, air masses which acquire their characteristics from heating at the surface are usually deep. When Polar Continental air moves out over the northern Pacific Ocean it is heated from below. As a result, vertical currents are set up and the heat and moisture acquired at the surface are carried aloft. Air masses acquire the characteristics of their sources much more quickly when they are heated from below than when they are cooled from below.

II. CLASSIFICATION OF AIR MASSES

Air masses are classified according to *source regions.* The source regions are those sections of the earth's surface where air tends to stand and assume the properties of the surface. Such source regions lend their influence in determining the humidity and temperature of the air masses. Because the thermal condition of these source regions varies with the season, air masses which obtain their characteristics from such areas also vary. *However, in general, air from tropical regions is warm, and air from polar regions is cold.* The humidity of an air mass is largely dependent upon whether it is of continental or maritime origin. *Again, in general, continental air is dry and mari-*

time air is moist. Air masses are also given a thermodynamic classification. An air mass colder than the surface over which it is passing is classified as a thermodynamically cold air mass. An air mass warmer than the surface over which it is passing is classified as a thermodynamically warm air mass. Air warmer than the surface over which it is passing is designated by the symbol w. Air colder than the surface over which it is passing is designated by the symbol K. Thus, Tropical Gulf air warmer than the surface over which it is passing would be designated as GTw.

III. MODIFICATION OF AIR MASSES

When air masses start to move they are influenced strongly at the surface by the type of terrain over which they travel. The weather to be expected in an air mass depends, to a considerable extent, on its life history. The life history of an air mass is dependent on the source

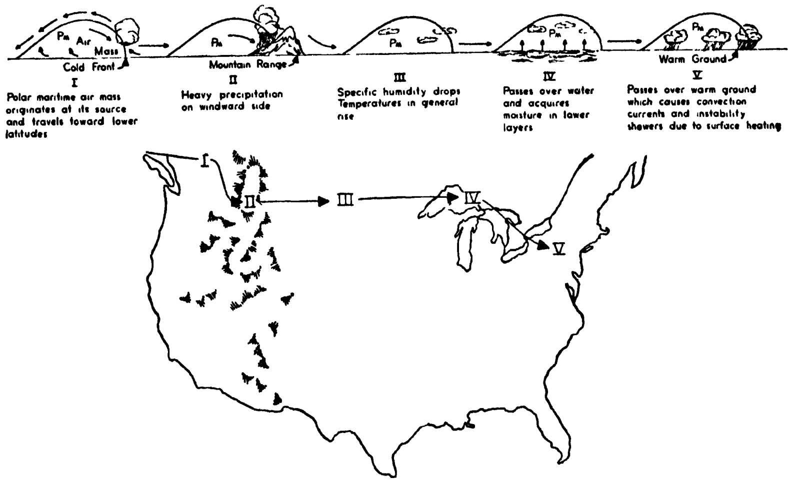


Fig. 56. Life history of a typical Maritime Polar air mass.

where it obtained its original properties, the path over which it has traveled and the time it has spent on its journey. In the summer, air from maritime sources is usually cooler than land areas over which it may pass. In the winter, continental air masses are usually colder than any water area over which they pass. Since the converse of the above is also true the characteristic weather to be expected in an air mass varies from summer to winter. For example, Tropical Gulf air masses from the Gulf of Mexico are warmer than the land over which they pass when they move northward during the winter. As a result they cool from below, become stable and develop low stratus clouds

or fog. In the summer, air masses from the same source region, as they go northward and pass inland over the heated continental area, are heated from below. During the summer such Tropical Gulf air masses often develop instability, cumulus or cumulonimbus clouds and thunderstorms. (Fig. 56)

A. Surface Heating. Surface heating raises temperature further above the dew point; hence, the air near the surface usually becomes dry. For example, if the dew point of an air mass was 12° C. and the temperature was only 13° C., the relative humidity would be high. If this air mass were heated at the surface to 20° C. and no moisture were added, the dew point would remain at 12° C. and the relative humidity would decrease without either the addition or deletion of moisture. Heating of the air at the surface also tends to bring about strong, adiabatic or superadiabatic lapse rates and instability. If the air mass has a high specific humidity the resulting thermals arising from the instability will be topped with cumulus or cumulonimbus clouds. Obviously, the higher the specific humidity the lower will be the level at which convective clouds will appear. Since instability brings about vertical mixing the collection of dust in the lower layers will be prevented, as well as the formation of low-lying stratus clouds, and, in general, the visibility will be good.

B. Surface Cooling. Surface cooling prevents or inhibits convection currents. Such cooling is confined near to the surface. The lapse rate tends toward stability and inversions often occur. Cooling may also produce condensation in the form of dew, mist, fog, or low turbulence clouds. Drizzle may occur if humidity is sufficient. Due to the absence of vertical currents when an air mass is warmer than the surface over which it is passing, dust particles, smoke and haze concentrate in the lower layers and the visibility is usually poor.

IV. THE GENERAL CHARACTERISTICS OF AIR MASSES

Due to a combination of circumstances, each individual air mass, as it has been recognized and classified, has been found to exhibit certain individual properties. On the other hand, there are certain properties which have been found to be common to polar air in general or Tropical Maritime air in general. These properties have been outlined in the following résumé:

A. Properties of Polar Air in General.

Temperature	Below that of the sea surface when blown to sea.
Humidity	Dry, especially near surface unless it is modified over the sea.

Stability condition in other than the source region	Unstable with convection currents, gusts, squalls, or bumpiness.
Weather after leaving source region	Fair or showery. Possible thunder. Broken cumulus-type cloud.

B. Special Properties of Polar Maritime Air.

Temperature	May be warmer than land over which it passes in winter.
Humidity	Rather moist. Showery precipitation begins and ends abruptly and visibility is good in summer over the land.
Stability condition	Stable in summer near the coasts. Unstable in winter near coasts. May become stable through surface cooling in the winter inland. Most characteristically steep lapse rates, and instability in summer inland.
Weather	Variable sky. Fog or low cloud from surface cooling in winter over the land. Likely thunder, cloudy and instability showers in the summer. Turbulence, gusts, and squalls possible in the summer over the land.

After passing to low latitudes this type of air may return with surface characteristics similar to tropical air. (This returning polar air is often called subtropical air.)

C. Special Properties of Continental Polar Air.

Temperature	Very cold in winter. May become quite warm in summer.

Humidity	Usually very dry. Clouds usually high. Cumulus clouds.
Stability conditions	Unstable in winter. Steep lapse rates as the air travels to lower latitudes.
Weather	Little tendency toward instability showers. Too dry. May bring "cold wave." Maximum cloudiness in afternoon at time of maximum surface heating.

D. Properties of Tropical Air in General.

Temperature	Warm
Humidity	Moist. Poor visibility in winter over the land.
Stability conditions	Stable. Usually warmer than surface except in the summer over the land. Inversions in lower layer in winter over the land.
Weather	Cloudless or with turbulence cloud (stratus or stratocumulus). Fine weather in summer or fog, mist or drizzle in winter over the land.

E. Special Properties of Tropical Maritime Air.

Temperature	Warmer than surface in winter. May be cooler than surface in the summer.
Humidity	Very moist.
Stability conditions	Unstable in summer. Stable in winter.
Weather	Subject to low clouds, fog or drizzle. In summer may give cumulus clouds, possible thunderstorms.

F. Special Properties of Tropical Continental Air.

Temperature	Hot in summer.
Humidity	Not always moist. In the summer this air may be very hot and dry.
Stability conditions	Stable. Usually warmer than surface.
Weather	Not subject to low clouds or fog. In summer dry, with clear sky.

Tropical Continental air is not found, as a rule, in North America because of the limited extent of tropical land areas in this continent.

V. THE NORTH AMERICAN AIR MASSES

Willett, in his classification of North American air masses, has pointed out that it is practically meaningless to classify any air mass of this continent as either Equatorial or Arctic. Because all the gradations between true Equatorial and Tropical, as well as between Arctic and Polar are found there is but small value in differentiating between Arctic and Polar or Tropical and Equatorial air masses on North American weather maps. Willett has classified North American polar air mass types as: Polar Pacific, Polar Canadian or Polar Continental and Polar Atlantic. The tropical air masses have been classified as Tropical Pacific, Tropical Continental, Tropical Gulf, Tropical Atlantic and Tropical Superior. Krick distinguishes another polar air mass as Polar Basin. Since air masses acquire their properties both in their *primary source regions,* the territory of their origin, and in their *secondary source regions,* the territory of their modification, both of these source regions have been included in the following table:

A. North American Air Masses Classified.

1. Polar Continental (cP). The primary source region of this air mass is Alaska, Canada and the Arctic Ocean. It is modified over southern Canada, the United States and the north Atlantic. When it is found in these secondary source regions it is known as modified or transitional Polar Continental or Polar Canadian (cPK). On those occasions when its trajectory lies over the north Atlantic in summer it may be cPW.
2. Polar Basin (BP). The primary source region is the Great Basin of the western United States. It is modified over cen-

tral and eastern United States where it is called modified or transitional Polar Basin (BPw or BPK depending on the season). Characteristically this air is found over the United States periodically from October to April.

3. Polar Pacific (PP). Air from arctic sources receives its maritime characteristics over the north Pacific. Polar Pacific air is further modified over the western Pacific and the North American continent where it is identified as modified or transitional Polar Pacific (MPK or MPw depending on the season). Polar Pacific outbreaks occur throughout the entire year.
4. Polar Atlantic (AP). The primary source region of Polar Atlantic air is the colder portions of the north Atlantic Ocean. It is modified in the warmer portions of the north Atlantic and eastern United States (modified or transitional Polar Atlantic, APK or APw depending on the season). Periodic outbreaks of Polar Atlantic occur throughout the entire year.
5. Tropical Pacific (PT). The source region of Tropical Pacific and the Pacific Anticyclone coincide. The locale of both lie between California and Hawaii and latitudes 20° to 35° North. This air mass becomes modified over the colder regions of the north Pacific (modified or transitional Tropical Pacific, PTw). Tropical Pacific is only important to United States weather from October to March.
6. Tropical Gulf (GT). The Gulf of Mexico and the Caribbean Sea serve as the primary source region for Tropical Gulf air masses. They are modified over continental North America (modified or transitional Tropical Gulf, GTw in winter or GTK in summer over the land). Tropical Gulf is found throughout the entire year.
7. Tropical Atlantic (AT). Tropical Atlantic has a primary source region coinciding with the locale of the Azores High in the south Atlantic. Tropical Atlantic is modified over the United States and the north Atlantic (modified or transitional Tropical Atlantic, ATw in winter or ATK in summer over the land). Tropical Atlantic air may be found along the eastern coast of the United States periodically throughout the year.
8. Tropical Continental (cT). Tropical Continental is a rather unimportant air mass in North America because of the lack of a source region due to the orientation of the North American continent. As a result, it is primarily a summer air mass occurring from April to October when the

southwestern United States and northern Mexico are warm enough to serve as a source region.

9. Tropical Superior (sT). The northeastern sector of the Pacific Anticyclone, when it extends over continental North America, serves as a primary source region for an upper air mass above an altitude of 5000 ft. Subsidence effects within the anticyclone lead to the formation of Tropical Superior air. It is believed that the air which finally becomes a Tropical Superior air mass might be originally from equatorial sources in southern Mexico. Tropical Superior air may occur throughout the year but most characteristically when the Pacific Anticyclone is displaced inland over the continent in winter.

B. Properties of North American Air Masses. In addition to the general characteristics of typical air masses, North American air masses have certain individually identifying properties brought about by the terrain over which they pass and the trajectories taken. A qualitative presentation of these properties is pictured in the following drawings. In addition, the tables present a quantitative aspect for the various identifying characteristics for summer and winter at representative stations. In the tables the elevation in meters is the elevation above sea level. θ_e is the equivalent potential temperature on the Absolute scale. The humidity is given in terms of mixing ratio in the column W/g/kg. Lift indicates the number of meters that the air at any given level would need to be lifted to reach its LCL. A dry air mass necessarily has a large lift value. Thus, Tropical Continental would have to be lifted 1300 meters above the surface before clouds would form in the rising air parcels. In contrast, Tropical Gulf air over Miami, Florida, in summer would reach the condensation point if lifted only 200 meters beyond the surface. A critical study of the tables will help clarify the many statements in the drawings regarding the individual physical properties of the various air masses. It is recommended that these values be plotted on the pseudo-adiabatic chart so that the student will be able to demonstrate that the physical values given for each air mass definitely determine its characteristics.

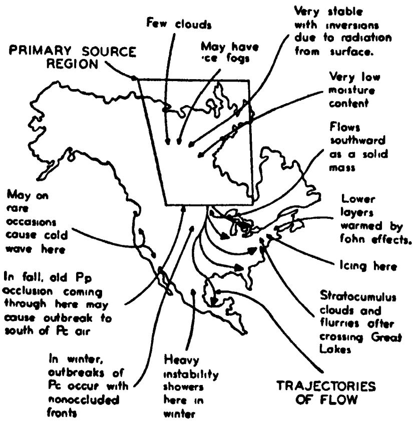


Fig. 57. Polar Continental Air in winter.

Typical Pc Air in Winter Fairbanks, Alaska							
Elev. Meters	Temp. ° C.	Temp. ° F.	D. P. ° F.	R. H. %	θ_e ° A	W g/kg.	Lift Meters
Surface	−41	−42	−55	44	233	0.1	
1000	−16	+ 3	....	40	270	0.5	1300
2000	−16	+ 3	....	30	277	0.5	1400
3000	−21	− 6	.. . .	27	280	0.3	1500
4000	−28	−18	.. ..	24	284	0.1	2200
5000	−35	−31	.. . ..	27	288	0.1	1500

Average Pc Air in Winter Ellendale, North Dakota							
Elev Meters	Temp. ° C.	Temp ° F.	D. P ° F.	R. H. %	θ_e ° A.	W g/kg.	Lift Meters
Surface (444)	−26	−15	−19	82	250	0.3	500
1000	−25	−13	....	82	256	0.4	500
2000	−20	− 4	... .	75	272	0.6	600
3000	−22	− 7	. .	63	280	0.5	800
4000	−25	−13	..	71	288	0.5	800

Average Pc Air in Winter Boston, Massachusetts							
Elev. Meters	Temp. ° C.	Temp. ° F.	D. P. ° F.	R. H. %	θ_e ° A.	W g/kg.	Lift Meters
Surface (4)	− 6	21	3	43	267	0.9	1400
1000	−14	6	....	50	268	0.6	1200
2000	−18	0	. ...	50	274	0.5	1200
3000	−23	− 9	....	44	279	0.3	1300
4000	−29	−20	....	48	283	0.2	1200

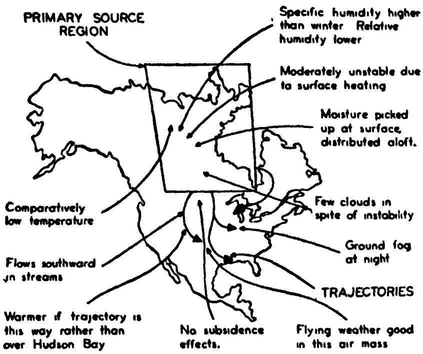


Fig. 58. Polar Continental Air in summer.

Average Pc Air in Summer
Ellendale, North Dakota

Elev. Meters	Temp. °C.	Temp. °F.	D. P. °F.	R. H. %	θ_e °A.	W g/kg.	Lift Meters
Surface (444)	19	66	43	42	312	6.3	1500
1000	16	61	....	45	313	5.6	1500
2000	10	50	....	43	312	3.9	1500
3000	4	39	.. ..	.44	314	3.1	1400
4000	−3	27	. . ...	57	318	2.9	800

Average Pc Air in Summer
Pensacola, Florida

Elev. Meter	Temp. °C.	Temp. °F.	D. P. °F.	R. H. %	θ_e °A.	W g/kg.	Lift Meters
Surface (4)	23	73	66	79	332	13.4	500
1000	20	68	....	65	330	9.8	900
2000	12	54	... .	67	325	7.2	800
3000	7	45	....	57	324	5.0	1000

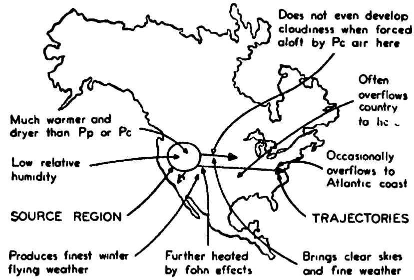


Fig. 59. Polar Basin Air (a winter air mass).

Typical Pb Air in Winter Salt Lake City, Utah							
Elev. Meters	Temp. °C.	Temp. °F.	D. P. °F.	R. H. %	θ_e °A.	W g/kg.	Lift Meters
Surface (1280)	− 2	+ 28	24	82	291	3.2	300
2000	+ 5	41	....	39	305	2.6	1600
3000	+ 2	36	....	31	309	1.9	1800
4000	− 4	25	....	25	313	1.2	2000
5000	−10	14	....	23	314	0 7	2100

Typical Pb Air in Winter Detroit, Michigan							
Elev. Meters	Temp. °C.	Temp. °F.	D. P. °F.	R. H. %	θ_e °A.	W g/kg.	Lift Meters
Surface (175)	4	39	32	75	289	3.9	500
1000	8	46	....	40	300	3.1	1500
2000	1	34	....	39	301	2.0	1500
3000	− 5	23	....	48	303	1.7	1300
4000	−11	12	....	74	309	2.0	500
5000	−18	0	....	88	311	1.7	200

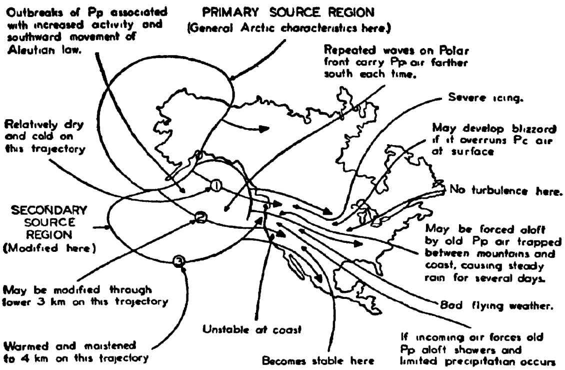


Fig. 60. Polar Pacific air masses in winter.

Typical Pp Air in Winter Fairbanks, Alaska							
Elev. Meters	Temp. °C.	Temp. °F.	D. P. °F.	R. H. %	θ_e °A.	W g/kg.	Lift Meters
Surface (150)	−14	7	6	96	262	1.3	0
1000	0	32	....	40	287	1.7	1400
2000	− 3	27	....	34	292	1.3	1500
3000	− 8	18	....	45	298	1.4	1200
4000	−10	14	....	80	310	2.1	500
5000	−15	5	....	85	314	1.9	300

Average Pp Air in Winter Seattle, Washington							
Elev. Meters	Temp. °C.	Temp. °F.	D. P. °F.	R. H. %	θ_e °A.	W g/kg.	Lift Meters
Surface (5)	8	46	36	66	292	4.4	700
1000	0	32	....	64	289	2.7	700
2000	− 8	18	....	64	288	1.5	900
3000	−14	7	....	52	289	0.8	1200
4000	−19	−2	....	35	294	0.4	1600

Average Pp Air in Winter Ellendale, North Dakota							
Elev. Meters	Temp. °C.	Temp. °F.	D. P. °F.	R. H. %	θ_e °A.	W g/kg.	Lift Meters
Surface (444)	− 1	30	26	83	284	3.0	300
1000	7	45	....	43	299	3.0	1400
2000	+ 1	34	....	44	300	2.2	1400
3000	− 7	19	....	48	301	1.5	1200
4000	−14	7	....	60	302	1.1	900

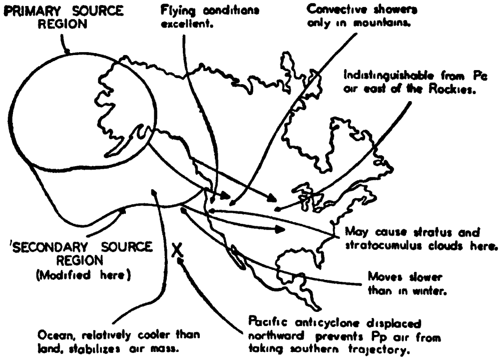


Fig. 61. Polar Pacific air masses in summer.

Average Pp Air in Summer Seattle, Washington							
Elev. Meters	Temp. °C.	Temp °F	D. P °F	R. H. %	θ_e °A.	W g/kg.	Lift Meters
Surface (5)	17	63	51	62	308	7.1	1000
1000	9	48		91	308	6	400
2000	5	41		60	307	3.9	900
3000	1	34	. .	42	309	2.3	1400
3500	−2	28	.	33	310	1.7	1600

Typical Pp Air in Summer Salt Lake City, Utah							
Elev. Meters	Temp. °C.	Temp. °F.	D. P °F.	R. H. %	θ_e °A.	W g/kg.	Lift Meters
Surface (1280)	16	61	43	53	322	7.1	1100
2000	21	70	. . . .	33	334	6.7	2000
3000	14	57	....	34	331	4.6	1900
4000	6	43	.. ...	43	332	4.1	1400
5000	−2	28	....	55	331	3.2	1000

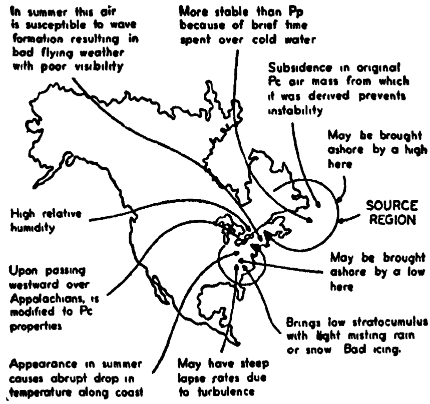


Fig. 62. Polar Atlantic air masses.

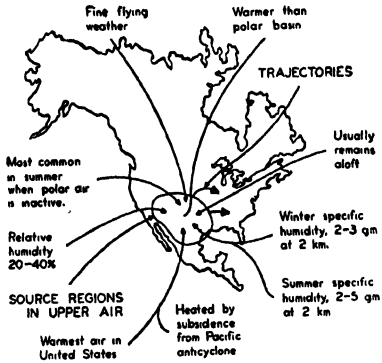


Fig. 63. Tropical Superior air masses.

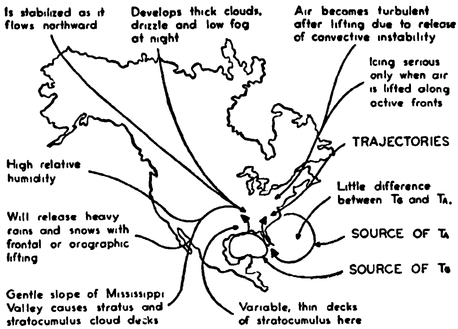


Fig. 64. Tropical Gulf and Tropical Atlantic air masses in winter.

Typical Tg Air in Winter
Miami, Florida

Elev. Meters	Temp. °C.	Temp. °F.	D. P. °F.	R. H. %	θ_e °A.	W g/kg.	Lift Meters
Surface (3)	25	77	71	82	343	16.3	400
1000	20	68	....	82	339	13.3	400
2000	13	55	....	83	333	9.8	400
3000	8	46	....	66	329	6.2	600
4000	3	37	.	67	332	5.2	600
5000	−4	25	....	37	326	2.1	1400

Average Tg Air in Winter
Royal Center, Indiana

Elev. Meters	Temp. °C.	Temp. °F.	D. P. °F.	R. H. %	θ_e °A.	W g/kg.	Lift Meters
Surface (225)	18	64	60	89	324	11.3	300
1000	13	55	....	96	322	9.6	100
2000	8	46	....	54	314	4.5	1100

Average TA Air in Winter
Boston, Massachusetts

Elev. Meters	Temp. °C.	Temp. °F.	D. P. °F.	R. H. %	θ_e °A.	W g/kg.	Lift Meters
Surface (4)	14	57	54	88	310	8.8	200
1000	14	57	....	59	314	6.5	900
2000	9	48	....	70	319	6.2	600
3000	2	36	....	75	318	4.6	500
4000	−4	25	....	65	319	2.9	700

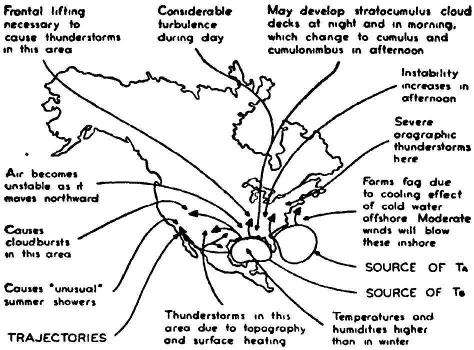


Fig. 65. Tropical Gulf and Tropical Atlantic air masses in summer.

Average Tg Air in Summer Miami Florida							
Elev Meters	Temp °C	Temp. °F	D P °F.	R H %	θ_e °A	W g/kg	Lift Meters
Surface (3)	24	75	73	93	345	17 3	200
1000	20	58	. .	88	346	14 9	300
2000	15	59	..	74	336	9 3	700
3000	9	48	.	58	333	5 3	900
4000	5	41	. .	48	331	4 3	1100
5000	−1	30		54	333	3 4	1000

Average Tg Air in Summer Broken Arrow, Oklahoma							
Elev Meters	Temp. °C.	Temp. °F	D P. °F	R H. %	θ_e °A.	W g/kg.	Lift Meters
Surface (233)	30	86	69	58	348	15.4	1200
1000	27	81		50	345	12 3	1400
2000	20	68		55	342	9 9	1200
3000	13	55	.	62	339	8.2	900
4000	7	45	.	53	336	5 4	1000
5000	2	36		41	336	3 5	1300

Average Tg Air in Summer Ellendale, North Dakota							
Elev. Meters	Temp. °C.	Temp. °F.	D P. °F	R. H. %	θ_e °A.	W g/kg	Lift Meters
Surface (444)	29	84	71	66	351	16 5	900
1000	27	81	.... .	54	346	13 3	1200
2000	22	72	.... ..	42	339	8.7	1600
3000	13	55	.	43	332	5 7	1500

Typical Tg Air in Summer San Diego, California							
Elev. Meters	Temp. °C.	Temp. °F.	D. P °F.	R. H. %	θ_e °A.	W g/kg.	Lift Meters
Surface (5)	22	72	71	95	338	15 3	200
1000	26	79	.. ..	53	347	12.6	1300
2000	18	64	....	70	344	11.1	800
3000	9	48	. ...	93	342	9.9	200
4000	2	36	....	96	338	7.3	100
5000	−3	27	....	92	338	5.0	200

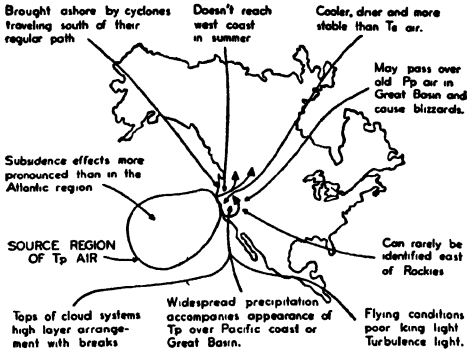


Fig. 66. Tropical Pacific air masses (reach the United States only during the winter due to the summer position of the Pacific anticyclone).

Average Tp Air in Winter San Diego, California							
Elev. Meters	Temp. °C	Temp °F	D P °F.	R. H %	θ_e °A.	W g/kg.	Lift Meters
Surface (5)	19	66	55	68	316	9.1	700
1000	17	62	.	47	315	6.1	1400
2000	11	52		51	319	5.3	1200
3000	5	41	. . .	50	318	3 7	1200

Average Tp Air in Winter Honolulu, T. H.							
Elev. Meters	Temp. °C.	Temp °F	D. P °F	R. H. %	θ_e °A.	W g/kg.	Lift Meters
Surface (3)	20	68	63	86	324	11.9	400
1000	15	59	. ..	81	325	9.8	400
2000	10	50	....	70	322	6.8	600
3000	6	43	. ....	51	320	4.0	1200
4000	1	34	. .....	33	320	2.1	1700
5000	−5	23	....	33	322	1.5	1700

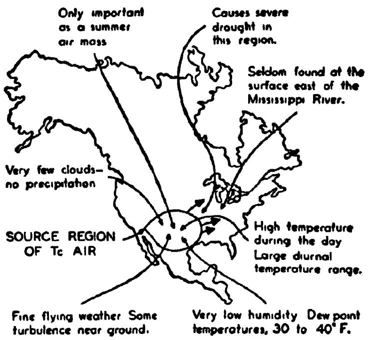


Fig. 67. Tropical Continental air masses (a summer air mass).

TYPICAL Tc AIR IN SUMMER
EL PASO, TEXAS

Elev. Meters	Temp. °C.	Temp. °F.	D. P. °F.	R. H. %	θ_e °A.	W g/kg.	Lift Meters
Surface (1190)	24	75	56	52	341	11.0	1300
1500	27	81	....	37	344	9.7	2000
2000	24	75	....	43	347	9.9	1700
2500	23	73	....	36	344	7.8	2000
3000	18	64	....	43	344	7.6	1600

AVERAGE Tc AIR IN SUMMER
BROKEN ARROW, OKLAHOMA

Elev. Meters	Temp. °C.	Temp. °F.	D. P. °F.	R. H. %	θ_e °A.	W g/kg.	Lift Meters
Surface (233)	27	81	53	40	329	9.5	1700
1000	27	81	....	32	332	7.9	2100
2000	19	66	....	33	330	6.5	1800
3000	10	50	....	46	327	5.0	1300

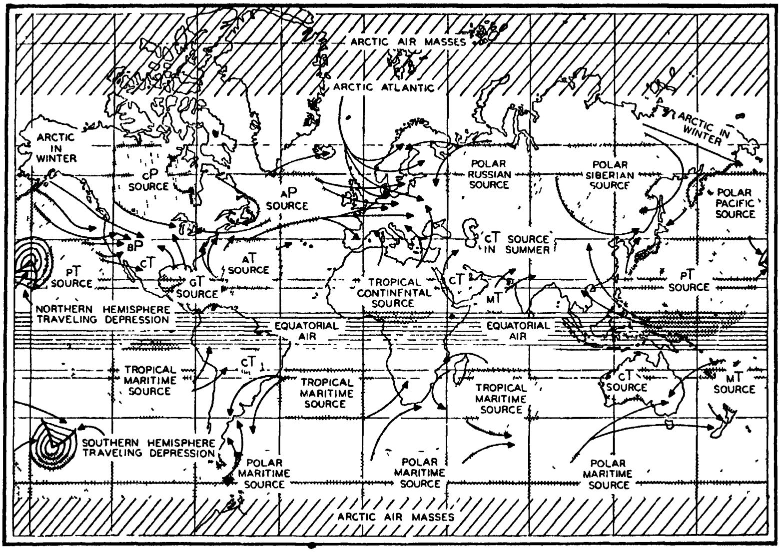


Fig. 68. Air masses of the world.

VI. EUROPEAN AIR MASSES

A. Arctic Maritime. This is the coldest of the maritime air masses. It is similar to Polar Continental air in its properties. A deep low, centered over the Scandinavian countries, will bring this cold air over the continent.

B. Polar Atlantic. Since Polar Atlantic air has crossed the north Atlantic, its properties are similar to Polar Pacific air on the west coast of North America. This air mass travels as far south as the Alps before it is modified to any extent.

C. Polar Russian. A low, centered over Scandinavia, and a high over northern Russia will feed this air mass into the European circulation. The properties are similar to Polar Continental air masses of the United States. Polar Russian air is a winter air mass in Europe because the deep lows, necessary to bring it into the European circulation, do not occur in summer.

D. Tropical Atlantic. Inasmuch as Tropical Atlantic, like Tropical Pacific, has traveled around the periphery of a high (the Azores High) it resembles the latter in its properties.

E. Tropical Continental. The broad expanses of the Sahara furnish an ideal source region for Tropical Continental air. Traveling lows bring this air into south and central Europe

Average $Ps_{\circ}$ Air in Winter Peiping, China							
Elev. Meters	Temp. ° C.	Temp. ° F.	D. P. ° F.	R. H. %	θ_e ° A.	W g/kg.	Lift Meters
Surface (70)	−12	+10.	−16	22	256	0.3	1700
500	−15	+ 5	....	24	261	0.3	1600
1000	−21	− 6	....	25	260	0.2	1500
1500	−25	−13	....	25	260	0.1	1400
2000	−30	−22	....	27	260	0.1	1300

Average $Ps_{\circ}$ Air in Summer Peiping, China							
Elev. Meters	Temp. ° C.	Temp. ° F.	D. P. ° F.	R. H. %	θ_e ° A.	W g/kg.	Lift Meters
Surface (70)	21	70	48	45	314	7.1	1300
1000	12	54	....	54	309	5.0	1000
2000	3	37	....	72	308	4.4	500
3000	−5	23	....	90	304	3.2	100

Average Tp Air in Summer Nanking, China							
Elev. Meters	Temp. ° C.	Temp. ° F.	D. P. ° F.	R. H. %	θ_e ° A.	W g/kg.	Lift Meters
Surface (70)	29	84	76	78	360	19.6	400
1000	24	75	....	71	348	14.6	600
2000	16	61	....	71	337	9.9	500
3000	9	48	....	76	332	7.4	400
4000	2	36	....	73	331	5.3	400
5000	− 4	25	....	70	329	3.5	500

VII. ASIAN AIR MASSES

A. Polar Siberian. The largest continental area of the world serves

as the source region for Polar Siberian air. Its properties are similar to North American Polar Continental. When it is carried over the North Pacific, by the circulation of the Siberian High, it returns as Polar Pacific. Reaction between Polar Siberian air and Tropical Pacific air causes much of the weather over south China, Japan and the Philippine Islands.

B. Polar Pacific. Polar Pacific may enter Asia as returning modified Polar Siberian around the periphery of the Siberian High. Again, Polar Pacific may be drawn over Asia by a deep low, centered over Japan and the China Sea. Asian Polar Pacific resembles North American Polar Atlantic.

C. Tropical Pacific. Tropical Pacific air in Asia resembles most closely North American Gulf. It may be drawn over south China by either cyclonic or anticyclonic circulations. Much of the weather of south China is due to the overrunning by Tropical Pacific air and often causes floods when present. When it fails to appear, droughts occur.

VIII. AUSTRALIAN AIR MASSES

Australia lies too far north to be in the general storm path of the Southern Hemisphere. Only in the winter do these frontal systems swing far enough north to influence the climate of this continent. Then, they strike mainly the south and west coasts. In the latitude of Australia and the neighboring oceans there is little interaction between air masses. Over the oceans adjacent to Australia the weather is typical of the trade-wind and high-pressure belts of the horse latitudes. As the air masses from the warm oceans blow over the Australian continent the moisture is deposited as orographic precipitation along the mountain ranges paralleling the coast. The interior of Australia is a good source region for Tropical Continental air.

IX. SOUTH AMERICAN AIR MASSES

Much of the weather along the east coast is due to an unusual synoptic situation. In the Southern Hemisphere the circulation around a high is counterclockwise. Tropical Maritime air, similar to the Tropical Pacific air of North America, circulates around the periphery of this high in the latitude of the horse latitudes. Other highs move northward along the east coast bringing Polar Maritime air. These two air masses converging give the unusual synoptic situation of a front between two highs. The typical frontal situation with warm fronts, cold fronts, warm sectors, etc., passes south of South America. This frontal type between highs develops into an occluded frontal situation.

X. SOUTH AFRICAN AIR MASSES

All of Africa except the most southern part is north of the Southern Hemisphere storm zone. In central Africa precipitation takes place from equatorial air. South of the equatorial zone, the zone of the horse latitudes precludes active air mass reaction. Further south in the Cape Province, typical Southern Hemisphere fronts pass through with interaction between Tropical and Polar Maritime air masses.

XI. CLOUDS

A knowledge of cloud types is useful to the meteorologist in many ways. As indicated in the previous analysis of air mass types and properties, clouds indicate the stability condition of an air mass. In the following chapter it will be demonstrated that cloud types also

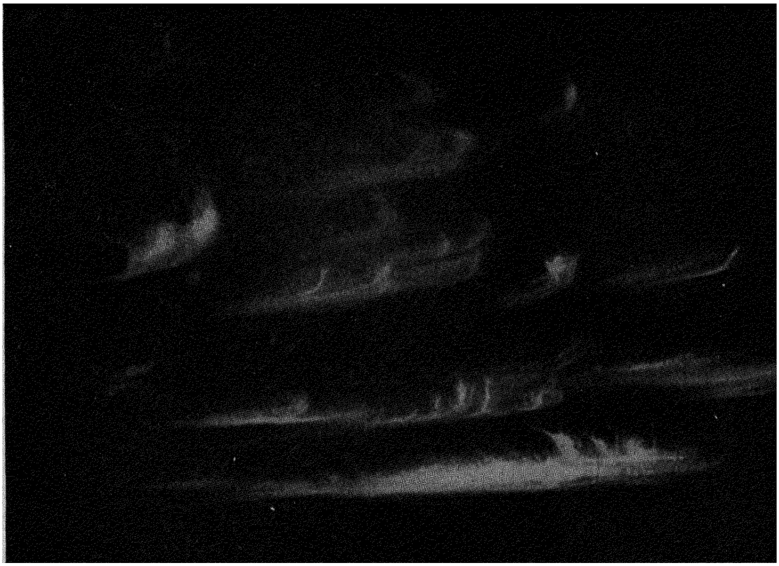


Fig. 69. Cirrus clouds (*cirrus uncinus* from International Cloud Atlas).

When cirrus clouds are arranged in bands they indicate an approaching warm front.

indicate the frontal activity, kind and amount. Clouds serve as the visible indication of weather trends to the experienced pilot. Local indications, as demonstrated mainly by clouds and cloud transformations, are very important to the forecaster as well. The reactions taking place in the laboratory of the sky are indicated by the multitude of cloud varieties and changes in their structure and appearance.

A. Classification. One of the most common forms of condensation is clouds. In the international system there are four families and ten genera of clouds, in addition to many species, varieties and special forms. In the winter clouds are usually lower and travel faster. In general, cloudiness is greater at night than in the daytime over land and greater in the winter than in the summer. Clouds may be classified on the basis of altitude as follows:

1. High Clouds (Altitude range of Family A at 40° N. Latitude 26,000 ft. to 32,000 ft.).
    a. Cirrus (Ci). Delicate wispy clouds. No shading. Usually white. (Fig. 69)
    b. Cirrocumulus (Cc). Rippled sand. No shading. Small white flakes or very small globular masses. (Fig. 70)

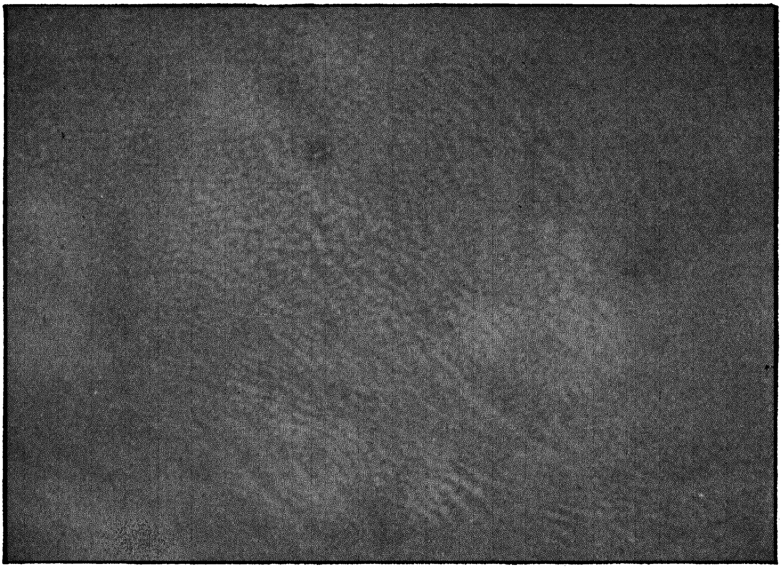


Fig. 70. Cirrocumulus clouds (*cirrocumulus undulatus* from International Cloud Atlas).

Cirrocumulus is usually derived from cirrus or cirrostratus. It is an uncommon cloud type.

    c. Cirrostratus (Cs). Very thin veil. Does not blur outlines of sun or moon. Gives sky a milky look; sometimes may show fibrous structure. (Fig. 71)

2. Middle Clouds (Altitude range of Family B 6000 ft. to 16,000 ft.).

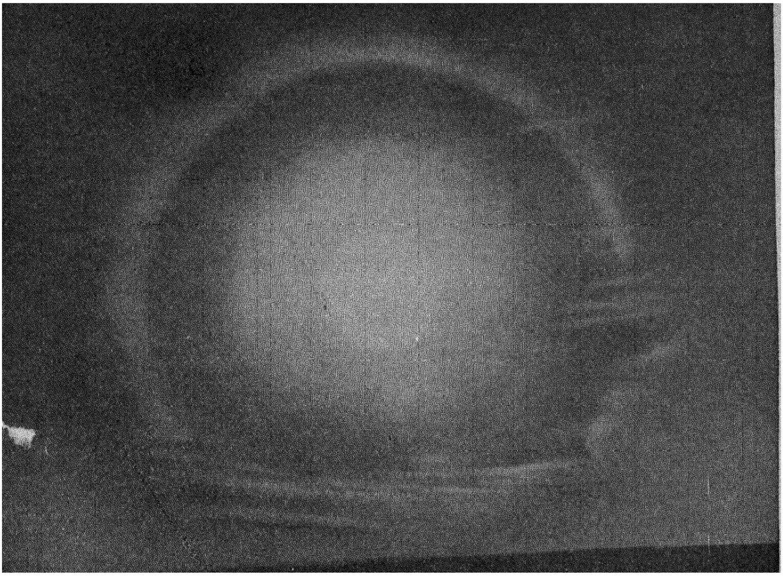


Fig. 71. Cirrostratus clouds (from International Cloud Atlas).

In the above illustration there is a halo around the sun. Cirrostratus clouds characteristically indicate the approach of a warm front.

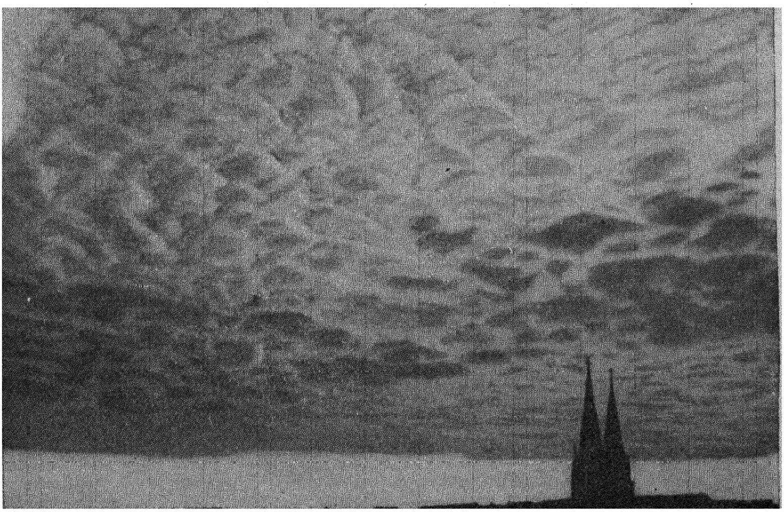


Fig. 72. Altocumulus clouds (*altocumulus translucidus* from International Cloud Atlas).

Altocumulus types may precede the cold front.

a. Altocumulus (Ac). Layer of flattened globular masses. Arranged in groups, lines or waves. (Fig. 72)

b. Altostratus (As). Blue-gray fibrous layer. Sun or moon shows dimly as through frosted glass. (Fig. 73)

3. Lower Clouds (Altitude range of Family C ground to 6000 ft.).

a. Stratocumulus (Sc). Layer of rounded masses.

b. Stratus (St). Uniform sheet, resembles fog.

c. Nimbostratus (Ns). Low, dark rain cloud.

4. Clouds with Vertical Development (Altitude range of Family D 1500 ft. at base up to Cirrus level). Cumulus (Cu) and Cumulonimbus (Cb). (Fig. 74)

B. Causes of Clouds. The main cause of clouds is the cooling of air below its dew point by reduction of pressure. There are three main types of vertical air movement contributing to the formation of clouds.

1. Nimbostratus and altostratus clouds are largely due to the slow upward movement of large air masses owing to orographic lifting or convergence in the horizontal motion of the air beneath. Such phenomenon often causes continuous precipitation.

2. Cumulus or cumulonimbus clouds are caused by the upward movement of small air masses. Cumulus clouds are associated with instability.

3. Stratocumulus, stratus, altocumulus, and cirrocumulus clouds are often caused by turbulence which distributes moisture into upper layers where condensation takes place. In many cases two or three of these types of vertical motion operate concurrently.

C. Meteorological Significance of Clouds. Cloud types are valuable in determining the probable nature of the overlying air mass. Warm, cold and occluded fronts are all accompanied and preceded by typical cloud sequences.

XII. OTHER FORMS OF CONDENSATION

A. Dew and Frost. Dew does not fall. It forms on a cool surface such as green vegetation, which is cooler than the surrounding air. Frost is formed in the same manner. However, the surface is so cold that vapor in the air sublimates to form ice directly without going through the vapor stage. This direct transformation accounts for the crystalline structure of frost particles.

B. Precipitation Forms. All condensation does not result in precipitation. Precipitation only occurs when some form of condensation becomes heavy enough to fall earthward even through

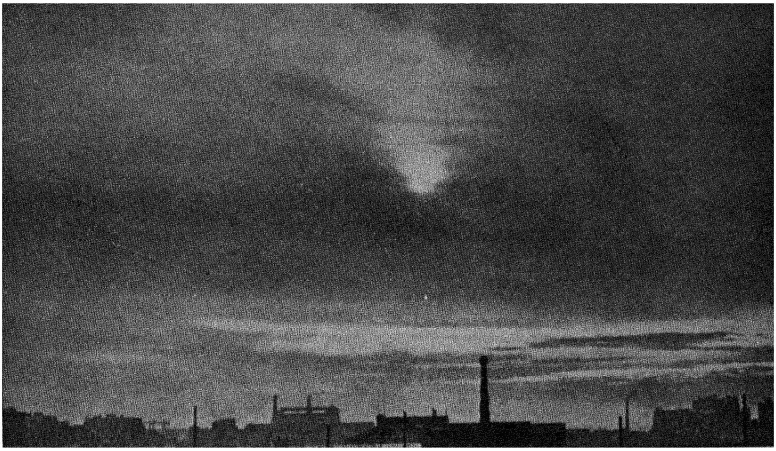


Fig. 73. Altostratus clouds (*altostratus opacus* from International Cloud Atlas).

Altostratus clouds typically just precede or accompany precipitation in advance of the warm front.

Fig. 74. Fine weather cumulus (*cumulus humilis* from International Cloud Atlas).

The lack of vertical development indicates stability aloft.

gentle ascending currents. The common forms of precipitation are rain, snow, hail, sleet and mist.

1. Snow. Both snow and frost are formed by sublimation. The crystalline structure of a snow flake is due to the method of its formation. Snow is formed in the air and falls to earth.
2. Sleet. Sleet may either be a mixture of snow and rain or rain which has partly frozen on its way earthward.
3. Mist. Mist, or drizzle, is formed in low clouds. The droplets are very small. They do not fall in large quantities or with great velocity.
4. Hail. Hail is formed characteristically in large cumulonimbus clouds where violent convection occurs. Liquid droplets are carried upward to where they can freeze. They then drop, only to be picked up by other currents and carried upward to freezing zones again. As a result hailstones have a layer formation. When they have become heavy enough to overcome the force of the vertical currents they fall to the ground.

C. Causes of Condensation.

1. Hygroscopic Nuclei. Sulphur dioxide, from various industrial processes, has been shown to be an excellent source for condensation nuclei. Sulphur dioxide, when exposed to sunlight, changes to sulphur trioxide which is unstable in the presence of water vapor. Sulphur trioxide attracts water vapor to it even at low humidities. Sea salt sprayed into the air has also been shown to be an excellent hygroscopic (a substance having an affinity for water) nucleus. It is believed that condensation is a continuous process. Even at low humidities the contention is that hygroscopic nuclei attract the water around them. As the relative humidity approaches saturation such nuclei continue to grow until a visible haze is formed and finally fog or cloud. Supercooled liquid droplets may be formed in clouds with temperatures as low as -20° to -30°. The existence of such supercooled droplets may be attributed to colloidal stability. Solidification occurs when such supercooled cloud masses are disturbed by turbulence. The passage of aircraft through supercooled liquid cloud masses results in icing.
2. Colloidal Stability. Water does not always precipitate upon condensation. Clouds are composed of liquid or solid particles of water. It is believed, that in the case of water clouds, the particles of liquid water are of nearly microscopic size. These particles are composed of aggregates of molecules with like charges residing on the particle. Since like charges repel, these colloidal particles tend to be sup-

ported in the air and are prevented from uniting to form larger particles by their mutual repulsion. This state of colloidal stability may be destroyed by introducing an unlike charge, hence, according to Bergeron, precipitation (rain, snow, etc.) is brought about when ice and water particles are found in the same cloud. Thus, cumulonimbus clouds develop into active thunderstorms when vertical convection has caused them to extend into altitudes where the temperature is below freezing. Cumulonimbus clouds which have reached the freezing level develop a mantel of cirrus nothus, an ice-crystal fragment cloud.

3. Bergeron's Hypothesis. The idea of colloidal stability in supercooled liquid cloud masses has led Bergeron to state that precipitation of appreciable quantity comes only from cloud masses in which supercooled liquid particles and ice particles exist concurrently. Ice particles cause precipitation to occur by serving as nuclei for condensation.

TEST QUESTIONS ON AIR MASSES

1. Surface heating of an air mass usually causes it to become (stable, unstable). 1. ________

2. Air masses that are thermodynamically warm are (stable, unstable) air masses. 2. ________

3. The symbols used to indicate Tropical Gulf air, which has become unstable due to surface heating, are ________. 3. ________

4. The source region for ________ air is in north central Canada. (Give symbols.) 4. ________

5. ________ type air, originally from Arctic sources receives its characteristic properties in the north Pacific. (Give symbols.) 5. ________

6. The warmest air mass in North America is (Tropical Gulf, Tropical Superior, Tropical Atlantic, Tropical Pacific). 6. ________

7. The following air mass acquires its properties due to subsidence. (Polar Pacific, Polar Atlantic, Polar Continental, Polar Basin). 7. ________

8. The following air mass acquires its properties due to subsidence. (Tropical Continental, Tropical Gulf, Tropical Superior, Tropical Atlantic). 8. ________

9. Select the air mass with the lowest humidity. (Tropical Pacific, Polar Continental, Polar Atlantic, Polar Pacific). 9. ________

10. In the winter (Polar. Continental, Polar Pacific, Tropical Gulf, Polar Atlantic) characteristically has deep inversions while over its source region. 10. ________

11. (Polar Continental, Polar Basin, Tropical Pacific, Tropical Superior, Polar Pacific) is unstable over its source region in winter. 11. ________

12. Air from maritime sources becomes more unstable as it flows inland in (summer, winter). 12. ________

13. Few clouds are formed in (Polar Pacific, Polar Continental, Tropical Gulf, Tropical Atlantic, Polar Atlantic) even when it is heated at the surface. 13. ________

14. (Fog, drizzle, stratiform, cirrus, cumulus) clouds are characteristic of an unstable air mass. 14. ________

15. The best winter flying weather is found in (Polar Pacific, Polar Atlantic, Polar Basin) air. 15. ________

16. Air masses formed by surface cooling are (deep, shallow). 16. ________

17. Convective clouds will form at (high, low) level when the specific humidity is high. 17. ________

18. Visibility is usually (good, poor) in unstable air. 18. ________

19. Tropical Superior air has a (high, low) relative humidity. 19. ________

20. The relative humidity of Polar Continental air is (higher, lower) in summer than in the winter. 20. ________

21. Polar Basin is (warmer, colder) than Polar Pacific air during the winter. 21. ________

22. Polar Pacific air may characteristically follow any one of (2, 3, 4, 5) different routes into the United States. 22. ________

23. (Tropical Gulf, Tropical Atlantic, Tropical Pacific) is a shallow air mass because of subsidence over its source region. 23 ________

24. The properties of Tropical Gulf are very similar to the properties of (Tropical Continental, Tropical Superior, Tropical Pacific, Tropical Atlantic, Tropical Saharan). 24. ________

25. Flying weather is usually (poor, good) in Polar Atlantic air. 25. ________

26. After passing over the Great Lakes in early winter Polar Continental air becomes (stable, unstable). 26. ________

27. Air mass thunderstorms are most likely to be found in (Tropical Gulf, Tropical Superior, Tropical Pacific, Tropical Continental) air in summer over the land. 27. ________

28. Fogs and low stratus clouds are not unusual in Tropical Gulf air over the land in (summer, winter). 28. ________

29. Tropical Atlantic air may develop sea fogs, which will move inland in the early morning during the (summer, winter). 29. ________

30. Tropical Pacific is an important air mass in the United States during the (summer, winter). 30. ________

31. Polar Pacific (often, seldom) plays an important role in the weather of Asia. 31. ________

32. Tropical Pacific (is, is not) an important Asian air mass. 32. ________

33. Tropical Continental (is, is not) an important Asian air mass. 33. ________

34. Probably the coldest maritime air mass in the world is ________ which overflows Europe during the winter. 34. ________

35. In Europe Polar Atlantic air is similar to (Polar Atlantic, Polar Pacific, Polar Continental) air in North America. 35. ____________

36. Polar Russian outbreaks characteristically occur over Europe during the (summer, winter). 36. ____________

37. Tropical Continental air from Africa usually enters Europe in the circulation of (highs, lows). 37. ____________

38. Weather along the east coast of South America often is the result of fronts formed between two (highs, lows). 38. ____________

39. Australia and Africa lie largely (north, south) of the Southern Hemisphere storm belts. 39. ____________

40. The circulation in Southern Hemisphere low-pressure areas is (clockwise, counterclockwise). 40. ____________

CHAPTER VII

TRAVELING DISTURBANCES AND FRONTS

1. CIRCULATION EFFECTS

Much of the weather in the temperate zones is due to the interaction of dissimilar air masses along discontinuity lines and surfaces known as fronts. The primary circulation, as modified by the centers of action, brings together large masses of air with differing physical properties when the circulation is converging. When winds from two or more directions approach the same point they are said to converge. The line, or surface, separating these dissimilar air masses represents the primary frontal zones. If the two air masses continue to flow side by side with no overrunning or underrunning between them, secondary traveling disturbances do not develop. When overrunning or underrunning starts to occur between air masses with different physical properties, then cyclogenesis takes place and typical traveling disturbances develop with warm fronts, cold fronts, occlusions and extensive accompanying weather phenomena. (Fig. 75)

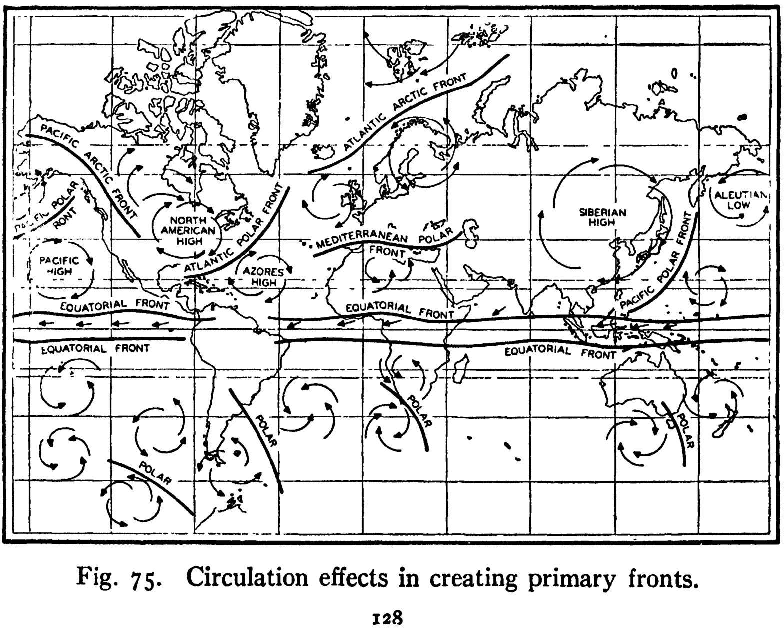


Fig. 75. Circulation effects in creating primary fronts.

II. THE DEVELOPMENT OF FRONTS AND TRAVELING DISTURBANCES (HIGHS AND LOWS)

A. Frontal Zones. The tendency of the primary circulation is to produce large air masses of approximately homogeneous properties. This same primary circulation also tends to produce frontal zones between the various air masses by bringing them into interaction. Wherever air currents converge together on a line such fronts are maintained.

1. Equatorial Frontal Zone. This is not a pronounced or important front since the temperature differences between its component masses are slight. The equatorial front is situated in the doldrums. The component air masses are the equatorial air masses and the subtropical air brought toward the equator by the trade winds.
2. Arctic Frontal Zone. This is a front that develops between the Polar Maritime air and the true Arctic air farther north. The circulation around the Aleutian and Iceland Lows brings Polar Maritime air poleward to the vicinity of the Arctic air of the polar easterlies.
3. Polar Frontal Zone. Particularly in North America, the most important frontal zone is the polar front. Along this front polar air masses and tropical air masses meet. The polar air breaks out (underruns) and often pushes far southward in winter. In summer the polar frontal zone recedes to the north. Traveling depressions (cyclones) develop along such fronts as the above. These cyclones derive their energy from the tremendous heat energy sources due to temperature differences found at such *primary fronts.*

B. Frontal Type Depressions (Lows or Cyclones). In the Northern Hemisphere when wave formation takes place along a primary front, a low-pressure area is formed into which the winds converge in a counterclockwise direction. In the Southern Hemisphere winds blow clockwise in a low.

1. General Characteristics of a Low. The diameter of the extratropical cyclone (depression, low) varies from 100 to 2000 miles. The average diameter of such disturbances is about 1000 miles. The general outline of these storms varies from approximate circles to elongated ovals. Such traveling disturbances may have V-shaped depressions (a trough of low pressure) particularly at the fronts. In the Northern Hemisphere winds blow inward, counterclockwise, at angles of 20° to 40° to the isobars. The warm sector is in the southern or southeast quadrant of a low. The winds are southerly in this sector. The northern, northeastern and western portions are cooler. In general, cloudiness and pre-

cipitation are associated with the movement of lows, particularly around the frontal zones. (Fig. 76)

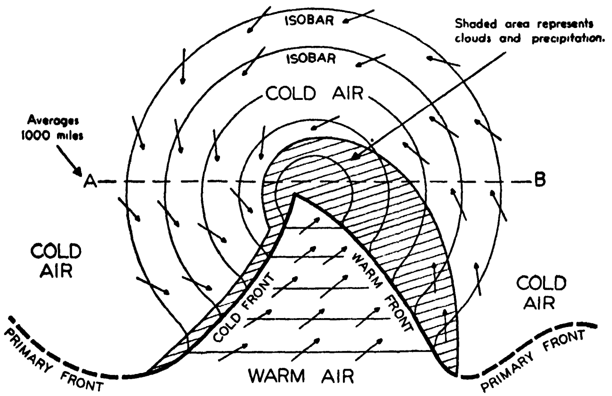


Fig. 76. An extratropical cyclone of the Northern Hemisphere just before occlusion (arrows indicate wind directions).

2. Origin (Frontal Theory). In North America traveling disturbances often originate as wave disturbances along the polar front. They are composed of vortexes of converging air with active fronts between the reacting air masses. Energy is furnished by thermal differences in the composite air masses. Such disturbances travel from west to east along the original parent primary front.

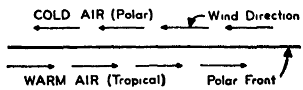


Fig. 77

a. *Original Condition along the Polar Front.* In the above example, wind is circulating in opposite direction in the opposing air masses. The zone of separation between the dissimilar air masses is the polar front.

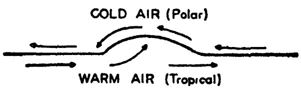


Fig. 78

b. *The Beginning of a Wave Motion along the Front.* Because of some thermal irregularity, or possible top-

ographical difference, the warm air mass will start to swirl into the cold air mass and the cold air mass will start to swirl into the warm air.

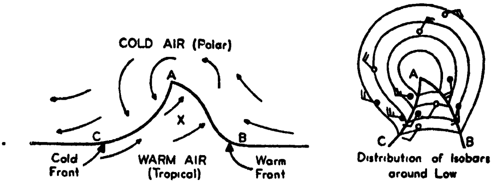


Fig. 79. The frontal disturbances.

c. *The Two Air Masses as Developed into a Definite Wave.* This wave will continue its development and travel along the polar front from west to east. The frontal section along AB where the warm air is overrunning the cold air is called the *warm front.* The frontal section along AC where the cold air is underrunning the warm air is called the *cold front.* The area CAB at X where the warm air is being pocketed is known as the *warm sector.* The lowest pressure will be at A with pressure increasing outward. The isobars in the above example represent a possible pressure dis-

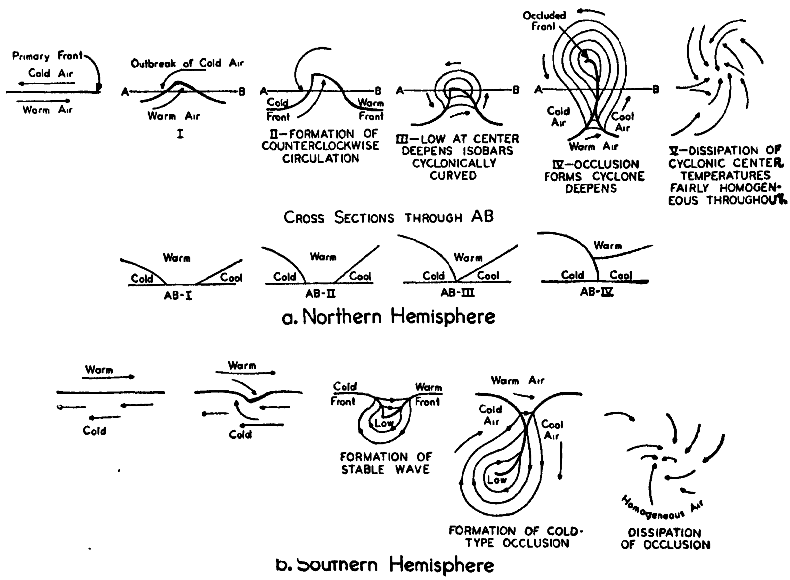


Fig. 80a and b

tribution around the frontal system. This whole system constitutes the traveling disturbance known as a frontal depression (extratropical cyclone or low). When the frontal cyclone becomes unstable it occludes. The occlusion process is caused by the cold front overtaking the warm front and forcing the air in the warm sector entirely from the ground. (Figs. 80a and b)

C. Thermal Depressions (Nonfrontal).

1. Monsoon Lows. In regions where monsoons occur large areas of low pressure are characteristic. These low-pressure areas are nonfrontal in nature and tend to persist throughout the season of their occurrence.

2. Local Lows. Depressions of this type are usually limited in area and are of little significance in map analysis. They are caused by bodies of water, deserts, etc.

D. Depressions due to Vertical Instability (Nonfrontal).

Instability Lows. When instability showers break out over an area, the latent heat liberated may contribute to the development of a depression of considerable extent.

a. Polar Air Depressions. In this type of instability low, local showery rain is characteristic. There is little variation of wind with height as compared with the frontal-type depression.

b. Inland Sea Winter Depression. The winds in such depressions are cyclonic and cold-front phenomenon often precedes them. The winds are often erratic due to orographic and katabatic effects along the coasts. Bad weather often develops and persists. Many local depressions may develop.

c. Shallow Summer Depressions. At times when the pressure gradient is slight, surface heating may result in shallow depressions A current of cool air in the upper atmosphere which favors instability may result in thundery weather with the rapid development of these shallow depressions.

E. Orographic Depressions (Nonfrontal).

Depressions due to Mountain Barriers. When the flow of the wind is interrupted by a mountain barrier, depressions often develop on the lee side of the mountains. With the passage of a cold front this process is accelerated. Warm air is often trapped at the lee side of the barrier. Occluding processes of this nature may lead to an intensive development of such depressions. (Fig. 81)

F. Source Regions for Cyclogenesis. As previously explained, frontal lows originate as waves along the major primary fronts.

Many circumstances may lead to cyclogenesis and frontogenesis. (*Cyclogenesis* is the formation of a frontal-type extratropical cyclone or low. *Frontogenesis* is the formation of active fronts). The semipermanent low-pressure areas, such as the Aleutian and

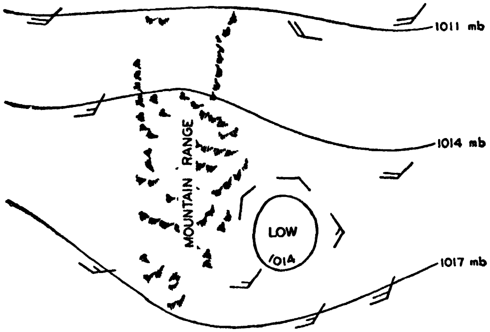


Fig. 81. An orographic low.

Icelandic Lows, serve as the original generating area for many traveling depressions or lows. Lows originating in the vicinity of the Aleutian Low often go through the preliminary stages and arrive on the west coast of the United States as occluded lows. (Fig. 82) These occlusions may be regenerated as they pass over

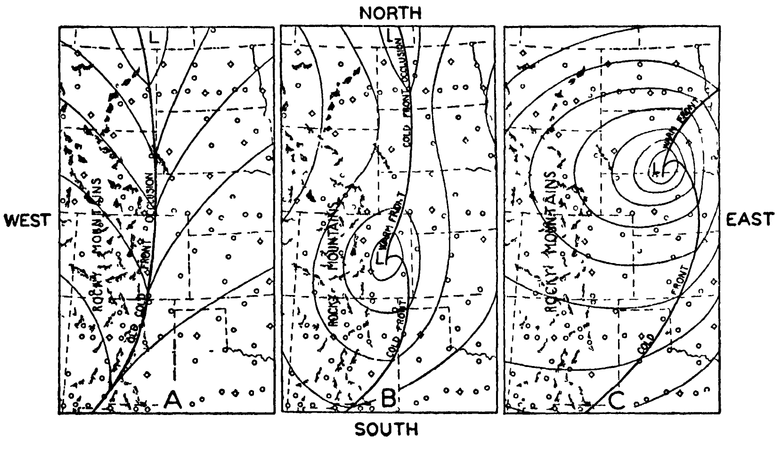


Fig. 82. The regeneration of an old occlusion.

the Rocky Mountains thus bringing maritime air into reaction with continental air masses or tropical air from the Gulf of Mexico. In other cases the pressure distribution may be such

as to bring warm moisture-laden air into active contact with colder air masses, and frontogenesis may take place in Texas or along the east Gulf and south Atlantic. China and the Philippine Islands also serve as important regions for cyclogenesis. (Fig. 83)

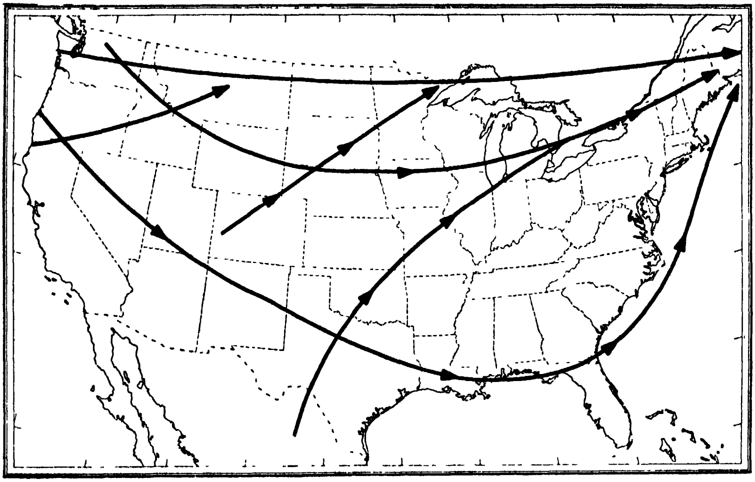


Fig. 83. Typical paths of extratropical cyclones in the United States.

G. Anticyclones (Highs). An anticyclone is an area of relatively high pressure. On the synoptic chart a high pressure area is enclosed by isobars. In areas where the air is diverging at the surface, high pressures are found at the center of the wind system. In high-pressure areas the air is settling from above and, as a result, inversions, or weak lapse rates, are common aloft. Subsidence and the consequent adiabatic heating tends to dissipate any high or middle clouds that might be present and, as a result, fine weather is characteristic of high-pressure areas. In the Northern Hemisphere winds blow spirally outward in a clockwise direction from the center of a high. In the Southern Hemisphere the winds blow counterclockwise from a high. Anticyclones do not always bring fair weather. Anticyclonic regions may be penetrated by fronts from adjacent low-pressure areas. As highs travel over oceans or warm continental areas, convective showers may develop. Anticyclones, undergoing anticyclolysis (dissipating), may have unsettled or bad weather in certain areas.

1. Origin of Highs (Polar Front Theory). The origin of anticyclones is controversial. However, one theory of their

origin is in general agreement with the polar front origin of lows. (Fig. 84)

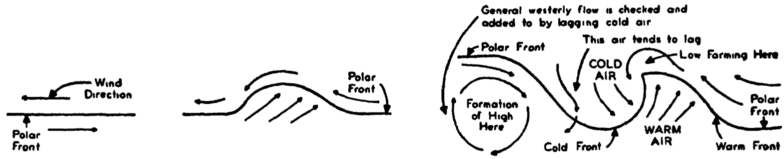


Fig. 84. The origin of transitory highs.

The general ~~circulation in the~~ United States is from west to east (prevailing westerlies). According to the above theory the development of a depression wave along the polar front results in an interference in the general primary circulation and the development of an anticyclonic circulation such as is shown in Fig. 84. More specifically, what occurs is that the more westerly part of the cold current is but little affected by the low pressure of the cyclonic low-pressure swirl and tends to lag behind. The result is a tendency to pull away from the cyclonic circulation and join another circulation. The westerly winds are underrun and partially checked, thus causing a local increase in pressure. The greater density of the cold air flow adds to the effect causing anticyclogenesis. Highs formed in this manner tend to move forward at the rear of the cyclone with which it initially began.

2. Subsidence Theory of Anticyclonic Origin. Another theory of the origin of anticyclones (highs) maintains that air in settling from upper-altitude circulation (subsidence) creates high-pressure areas. Such high-pressure areas are represented by the Pacific and Azores High, as well as the Southern Hemisphere oceanic high-pressure zones in the horse latitudes. This type of high is believed to have high vertical development. High-temperature highs extend to much higher altitudes than low-temperature highs.
3. Air-mass Highs. Another type of anticyclone, or possibly a modification of the subsidence theory of anticyclonic origin, is the air-mass high. Air masses that collect over continental areas in winter become cold throughout the lower layers and, as a result, represent high-pressure areas relative to warmer air masses elsewhere. Permanent radiational-type highs are found over Greenland and the antarctic regions. The high pressure in these two areas is due to the prevailing low temperature. The low temperature

is caused by high altitude and free and abundant radiation from the snow surface through clear air which is kept free from clouds by subsidence. During the winter elevated and snow-covered regions develop similar highs which are usually smaller in extent and temporary. These highs may give rise to strong, cold, surface winds when they feed into transitory lows. Low-temperature highs are shallow in vertical development and do not extend to great heights. The above descriptions, however, represent simplifications of the prevailing theories as to the origin of highs. The exact explanation of the nature of their origin waits on more complete upper-air data. (Fig. 85)

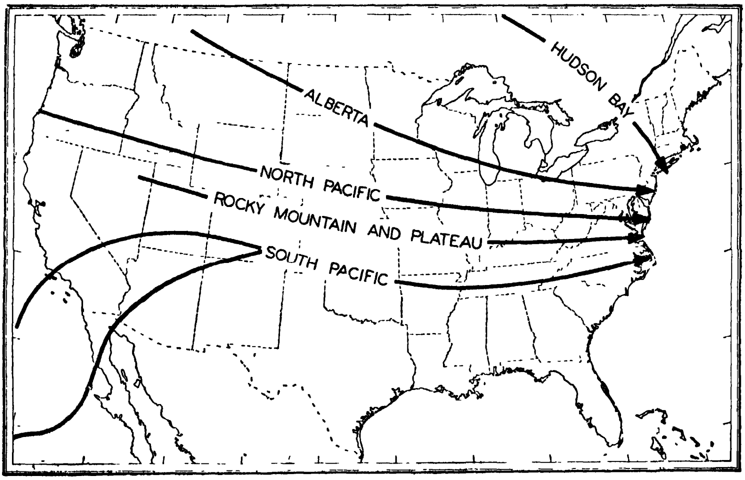


Fig. 85. The approximate paths and source regions of characteristic highs in the United States.

III. FRONTS AND THEIR CHARACTERISTICS

As previously demonstrated, the large traveling storm areas known as extratropical cyclones owe their existence to active overrunning and underrunning of warm and cold air. The lines, or surfaces, along which this interaction is taking place are the active fronts. The warm front is where the warm air has overtaken and overrun the retreating cold air. At the cold front, cold polar air is underrunning warm air from the tropics.

A. Stable and Unstable Waves. The simplest type of frontal activity, resulting in the generation of extratropical cyclones, is that of the stable wave. Such wave motion set up along a major primary front resembles water waves which have not grown

high enough to break at the top. For example, long, even swells coming in at the seashore are stable waves with a definite wave length until the time that they become breakers with white foam-tipped and wind-tossed tops. So in the case of atmospheric frontal waves when they consist of merely a warm front and a cold front, with an area of low pressure at their junction, they are known as stable waves. A stable-wave cyclone changes its structure very little during its history unless it becomes occluded. If a stable wave occludes it becomes an unstable wave and the pressure at the center of the low will continue to drop (deepen) and the cyclone will go through a rather complicated life history. If the wave remains stable, it will move along the primary front at a fairly constant velocity. If the frontal system occludes its velocity will vary, the rate being dependent largely on the stage of its development. The weather associated with either stable or unstable frontal-system waves is a function of the properties of the interacting air masses. Frontogenesis is usually first indicated by the appearance of an isallobaric low along a front and converging winds. (An *isallobar* is a line drawn between points of equal barometric tendency. For example, all of those stations reporting an increase of one millibar in three hours might be connected by a dotted line. This line would be an isallobar.)

B. Warm Front Characteristics. Along the cold front, cold air overtakes the warm air and forces it upward. On the other hand, at the warm front, warm air overtakes and overrides the cold air.

1. One of the most characteristic phenomena of warm fronts is the sequence of cloud types. Inasmuch as the warm air that is overriding the retreating cold air reaches its highest altitude at the maximum distance ahead of the surface front, it is here that high-altitude cirrus clouds are formed. This overriding may cause the formation of prefrontal cirrus as far as 600 miles ahead of the surface front. While the overrunning of the cold air by the warm air is believed to be the indirect cause of the formation of cirrus clouds, it is not generally held that they are formed within the ascending warm air. Rather, it is believed that the cirrus are formed as a result of the forced ascent of upper layers due to the overrunning process. This reasoning is supported by the fact that both cirrus and cirrostratus clouds extend back into the air of the warm sector. The discontinuity surface of the warm front merely marks the boundary of the cirrus-type clouds. The first indication of the approaching warm front is the appearance of cirrus clouds of the banded type such as cirrus radiatus and cirrus filosus. These are followed by cirrostratus (cirrostratus filosus or cirrostratus

lenticularis) with the banded arrangement orientated in a different direction. The first clouds actually formed in the overrunning warm air are the altostratus which precede the ideal warm front by about 300 miles. The average frontal slope of a warm front is about 150 miles horizontal for each mile vertical. Warm fronts are heralded by cirrus clouds followed in succession by cirrostratus, altostratus, nimbostratus, and finally by stratus.

2. Due to the action of surface friction the retreating cold wedge in advance of the warm front may tend to flatten. Thus, for some distance ahead of the surface front the slope of the discontinuity surface may be negligible. Often at some point well ahead of the front the slope of the discontinuity surface may rise abruptly giving the appearance of another front. Such false fronts are arrived at often particularly on the basis of precipitation areas as they appear on the synoptic chart. (Fig. 86)

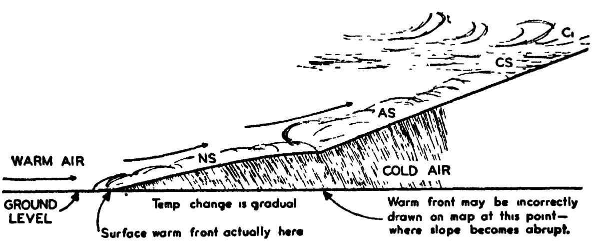


Fig. 86. A warm front with sudden change of slope.

3. Abrupt temperature changes like those at a cold front are not characteristic of the warm front. Through the zone where the retreating cold wedge is thin the temperature change is gradual. Hence, warm fronts can seldom be recognized on the synoptic weather chart on the basis of sudden temperature changes alone. If the current of warm air overrunning the cold wedge is conditionally unstable, warm-front thunderstorms may result. If the warm current is convectively unstable the lifting of layers may lead to voluntary convection and consequent shower-type precipitation. Again, continuous cloud layers are not always found preceding the warm front. The warm, ascending air may at times have varying properties. In such cases two or more waves of clouds may precede the front with intervening clear sections. When the discontinuity surface between the warm and cold air masses is uneven with waves along its surface the lifting along the surface results in uneven precipitation.

Since the rainfall characteristic of the ideal warm front is steady and increasing as the front is approached from the cold side, uneven precipitation must be associated with lifting over a varying slope. If the air being lifted along the frontal slope is not homogeneous, but stratified with the different strata having varying humidities, the prefrontal cloud continuum may be broken with patches of clear sky intervening between the various characteristic cloud sequences.

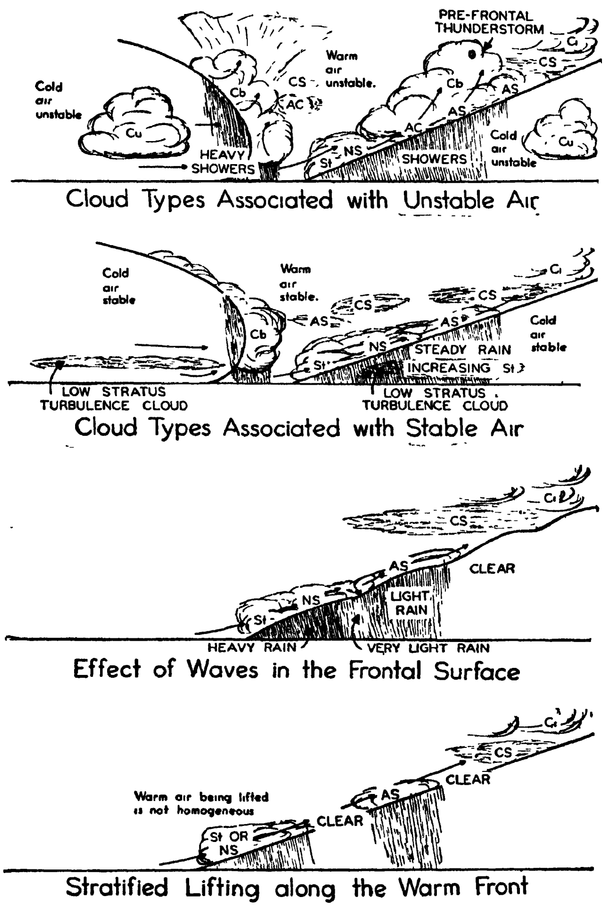


Fig. 87. Effects of frontal lifting.

4. In addition to the clouds found along the discontinuity surface between the warm and cold air masses, other cloud types are found in the cold air mass itself. When the lower

layer of cold air has passed over extensive water areas, stratocumulus clouds may form at a height of 1500 ft. Any precipitation from clouds formed under these conditions will probably amount to nothing more than drizzle. Scud clouds often form in the lowest layers due to turbulent mixing. (Fig. 87)

5. In identifying warm fronts on the weather map, it must be remembered that the wind discontinuity may not be sharp and the temperature transition may be gradual. However, the gradual temperature changes will occur in the transition zone entirely within the cold air. In the warm sector meteorological elements should remain fairly constant. The warm front may be recognized on the synoptic chart by a rise in temperature, a slight wind shift usually less than 45°, a slight barometric trough, and a small isallobaric discontinuity. The frontal passage is followed by clearing weather conditions and a rise in specific humidity. Icing conditions, high-level thunderstorms and moderate turbulence may be found in flying through warm fronts at various seasons of the year.

C. Cold Front Characteristics. The area of stormy weather at the cold front is limited in extent. Due to strong lapse rates and general instability conditions the weather at the cold front is characteristically squally. The *squall head* is caused by the retardation of the surface wind by friction between the cold air and the surface, while aloft these effects are minimized and the air surges ahead of the surface front. The elevation of the foremost part of the squall head averages about 1500 ft. The cold currents of the squall head may run as far as 100 miles ahead of the actual surface front; however, the average overrun is about 25 miles. (Fig. 88)

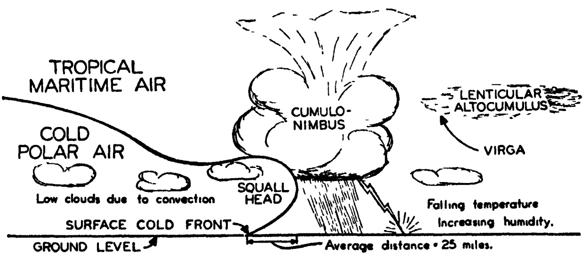


Fig. 88. Cross section of a cold front with a squall head.

1. Rain that precedes the arrival of the surface front is known as prefrontal rain. The character and amount of the

precipitation at a front is dependent on the nature of the air in the warm sector. If the air being forced upward at the cold front is modified polar air no precipitation may result at the cold front as the air will probably be too dry due to its original properties and also because of former precipitation within the mass. On the other hand, if warm, moisture-laden, conditionally unstable air is forced upward, cumulonimbus clouds may be formed with characteristic frontal thunderstorms resulting. This often happens when Tropical Gulf air is lifted along a frontal surface in summer. The approach of a cold front is relatively unheralded by clouds or precipitation. The first sign of an approaching cold front is the appearance of altocumulus or altostratus clouds. The cloud ceiling drops rapidly as the front approaches. Along the discontinuity surface the clouds are usually convective types such as cumulus and cumulonimbus. In the cold air following the discontinuity surface convergence or turbulence may produce stratus-type clouds. Whether the cold front will be preceded by altostratus or altocumulus depends largely upon the stability of the warm air mass. Virga (wisps or falling trails of precipitation) may frequently be observed in connection with the altostratus and altocumulus clouds preceding the surface cold front. The temperature often falls in advance of a cold front due to the evaporation of prefrontal rain. Hence, an increase in the specific humidity and a falling temperature will often indicate the approach of a cold front. When the warm air preceding the cold front is conditionally unstable the precipitation may be largely of the prefrontal variety. This effect is due to the fact that the warm air is thrown upward by the abrupt slope of the approaching cold front so that it reaches its LCL and becomes unstable while cooling at the moist adiabatic rate. As a result, a convective cloud system is built up in advance of the discontinuity surface of the cold front and prefrontal precipitation occurs. When a cold front is retarded in the speed of its advance over the surface these convective effects are minimized. Slow-moving cold fronts will often assume characteristics similar to those of the warm front due to the backward overflowing of warm air over the underlying cold stratum. At times, sections of a cold front may reverse their direction and temporarily become warm fronts.

2. As the cold front passes, clearing normally takes place. The continuous cloud deck at the fronts quickly breaks up with its passage into cumulus or stratocumulus clouds. Any

low clouds found in the cold air mass following the cold front are due to convection within the cold air mass. Those low clouds near the front may be formed at the discontinuity surface between the cold air and the underrun warm air aloft.

3. As a cold front moves to lower latitudes its slope usually decreases bringing the overlying warm air close to the surface. In some cases the cloud deck may even touch the ground resulting in fog. This stratus cloud type of fog may be due to saturation of the lower air by falling rain, or the mixing of nearly saturated Gulf air with the cold polar air composing the thin wedge. In winter the above conditions often cause ice storms. Precipitation through the cold wedge is supercooled. It freezes immediately upon contacting cold surfaces and coats everything it touches with ice. Sometimes a cold front separates into two discontinuities. In such cases the air back of a cold front will subside and heat adiabatically. This subsidence in the rear of the cold front results in the formation of secondary fronts. (Fig. 89)

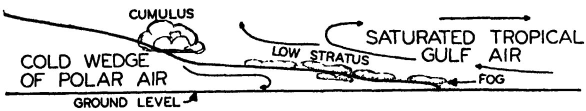


Fig. 89. Cross section of a cold front in low latitudes.

4. In general, the properties of a cold front may be summarized in the following manner: The slope of the discontinuity surface varies from one-mile altitude to every 30 miles in the horizontal, to one mile in 100. Thus, at a distance of 100 miles in the rear of a cold front the pseudo-adiabatic chart might show an inversion and an increase in mixing ratio value at an altitude of one mile as indicative of the cold front's discontinuity surface. On the synoptic chart the position of a cold front will be marked by an abrupt temperature fall, a well-marked windshift varying between 45° to 180°, a well-marked barometric trough, a decrease in relative humidity, a pronounced isallobaric discontinuity and a rather rapid improvement in weather conditions with clearing. If the cold front is moving at a fast rate a squall head will form due to the overrunning previously mentioned. Overrunning of this type produces violently unstable conditions since the warm air is being overrun by denser colder air which tends to change places with it. Violent turbulence and convection may result in

the production of a long line of roll cloud and the squally weather associated with the line squall.

D. Occlusions. When a cold front overtakes a warm front, occlusions occur and the air in the warm sector is forced aloft. Cold air is found both in front of the warm front and to the rear of the cold front. Usually there is a thermal difference between the cold air preceding the warm front and the cold air following the cold front. The thermal dissimilarity is, in most cases, caused by a difference in the amount of time that the two sections of cold air have been out from their source regions.

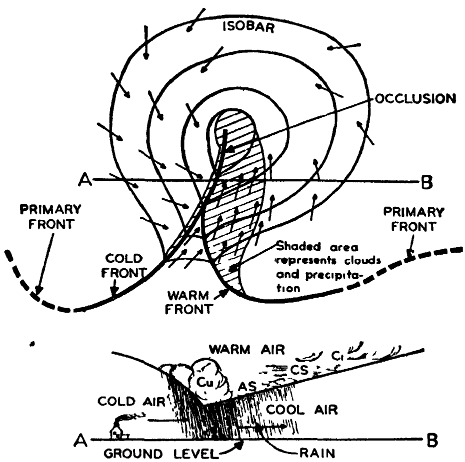


Fig. 90a. Occluded unstable wave (cold-type occlusion).

1. Cold-type Occlusion. If the air in advance of the warm front has a higher temperature than the air in the rear of the cold front, it will be lifted up along the slope of the overtaking cold front. As a result the weather of a cold-type occlusion is of a composite type resembling both warm and cold fronts. Along the slope of what was previously the warm front are found all the clouds associated with a warm front. The cold front has never left the ground but, on the other hand, the air being underrun is no longer warm, moist air from tropical regions and, hence, the frontal activity at the cold front, while it still persists, is modified. The source of supply of warm air has been cut off at the surface so that the air being forced along the old warm front is obtained only from that air trapped aloft. Nevertheless, extensive prefrontal precipitation is common although the area affected is less extensive than with a well developed warm front.

Behind the cold occlusion instability showers are common when the air is unstable. Typical cold-front weather is often found through a rather narrow belt in the immediate vicinity of the surface front of the occlusion. A cold-type occlusion may be preceded by stormy weather to a distance of 250 to 300 miles. After the occlusion is passed in going from east to west the weather usually clears rapidly. Since the cold front remains on the ground in the cold-type occlusion, they are represented on the synoptic chart as extensions of the cold front. (Fig. 90a)

2. Warm-type Occlusions. When the air in advance of the warm front is colder than the air following the cold front a

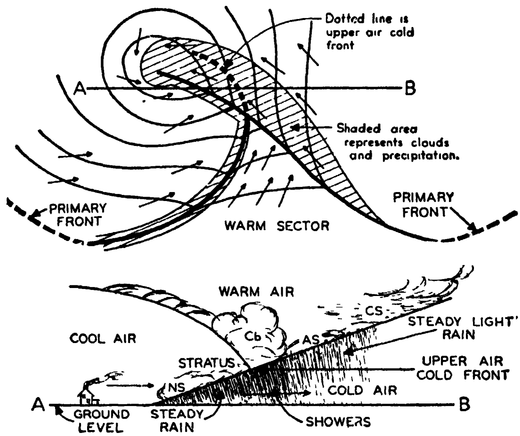


Fig. 90b. Occluded unstable wave (warm-type occlusion).

warm-type occlusion results when the cold front overtakes the warm front. In this case the overtaking air, being warmer and less dense, overruns the retreating, denser air, which was previously in advance of the warm front. The weather accompanying a warm-type occlusion rather closely resembles that of the typical warm front. It differs inasmuch as showery precipitation occurs from the old cold front which has now been forced aloft. The precipitation from the *upper air cold front* falls to the ground in advance of the occlusion at the surface. Showers from the upper cold front occur in a rather narrow band. Warm-type occlusions are frequent in the Pacific Northwest. In this region cold air is often trapped between the Rocky Mountains and the coast. Fresh outbreaks of maritime air overrun the entrapped cold air causing continued moderate or heavy

rain lasting for several days over this coastal area. Upper-air cold fronts are often hazardous to flight. Warm-type occlusions may often be recognized by the presence of an isallobaric discontinuity occurring some distance in advance of the surface occlusion marking the position of the upper-air cold front aloft. (Fig. 90b)

3. Bent-back Occlusions. In the last stages of the development of extratropical cyclones there is a tendency for

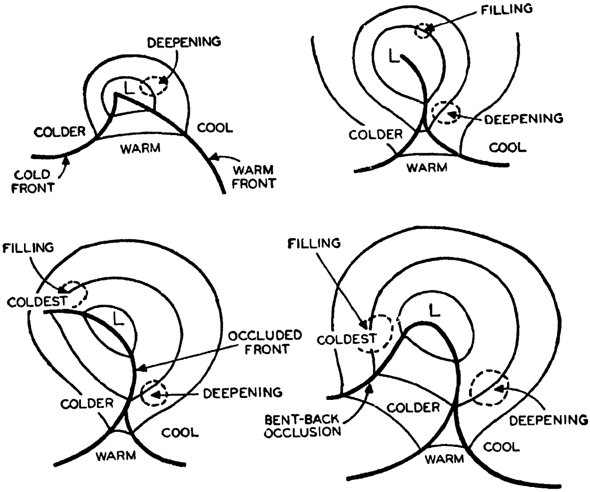


Fig. 91. Formation of a bent-back occluded front.

troughs of low pressure to form to their rear. The occluded front is often extended back into this trough on the premises that troughs of low pressure often occur at fronts and that the occlusion has been caught by the easterly and northerly currents in the cyclonic circulation and drifted back with the current. Most of the bent-back occlusions drawn on synoptic charts on the basis of the above premises are not really present in the weather situation. A true bent-back occlusion is found only under rather unusual circumstances. On partially occluded cyclones under certain conditions the old low-pressure center will fill (pressure is increasing at the center) while the junction of the branching warm and cold fronts starts to deepen (pressure is falling) and set up its own cyclonic circulation while occlusion continues. Thus, the old occlusion may be truly bent back by the newly generated circulation so that occlusion weather follows the cold front of the new cyclone. (Fig. 91)

4. Secondary Cold Fronts. Under some circumstances new cold fronts may be regenerated from bent-back occlusions. However, secondary cold fronts usually occur during outbreaks of very cold polar air over a warm surface. Secondary cold fronts may follow in succession at intervals of several hundred miles to the rear of a rapidly moving cold front. Again, secondary fronts may be formed by subsidence in the rear of a rapidly moving cold front. Under such circumstances the air is drawn downward toward the surface with the result that it is heated adiabatically. When this happens the original cold front undergoes frontolysis and is replaced by the newly generated secondary cold front. In the north central United States secondary cold fronts are often formed along the northern borders of the Great Lakes in winter. When these fronts sweep southeastward with the general circulation heavy snow flurries result. Secondary fronts usually do not occur during the summer since temperature contrasts are not great enough. (Fig. 92)

IV. IDENTIFICATION OF FRONTS ON THE WEATHER MAP

For the purpose of identifying fronts on the weather map the following sequence of relative importance of identifying characteristics has been developed.

A. Historical Sequence. Weather and fronts travel usually from west to east. Fronts and traveling disturbances will follow definite tempos across the country. Ordinarily fronts do not spring up or disappear immediately. Hence, the first and most important guide in drawing a weather map is what appears on the previous map. This idea of following logical, chronological succession is known as historical sequence.

B. Cloud Systems and Precipitation Areas. As has been demonstrated warm fronts are preceded by characteristic cloud formations. In the case of the warm front, precipitation is largely prefrontal. The precipitation is extensive, extending from 200 to 300 miles ahead of the actual front. Precipitation preceding the warm front is usually steady. In the case of the cold front, precipitation usually takes place over a rather limited area near the front. Squally weather is often associated with the cold-front passage. There is but little prefrontal cloud formation. Cirrus and cirrostratus clouds give the first indications of an approaching warm front. In ideal cases the cirrostratus shield precedes the central portion of the arc of the surface warm front by about 600 miles. The altostratus shield and the beginning of the pre-

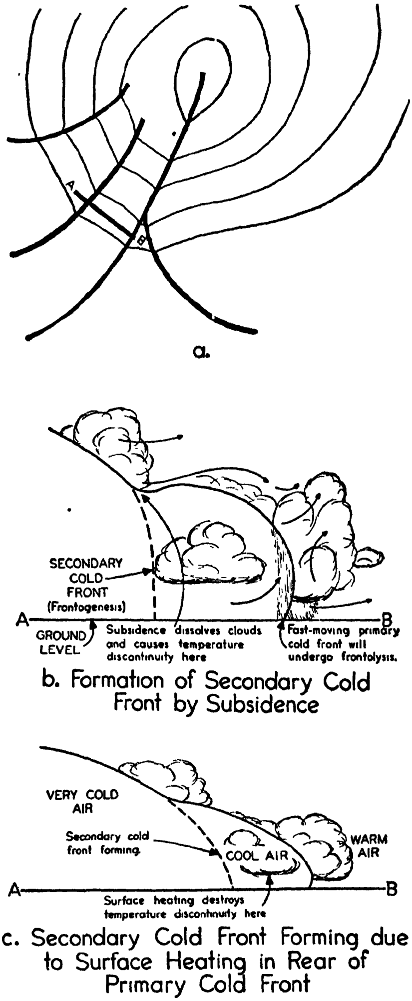
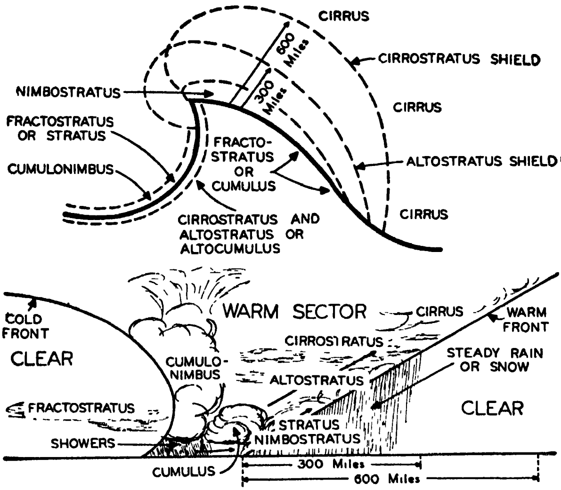


Fig. 92. Formation of secondary cold front by subsidence.

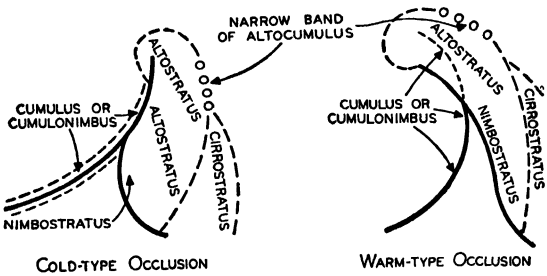
cipitation area lie about 300 miles in advance of the surface front. (Fig. 93)

C. Barometric Tendencies and Pressure Fields. These are outlined in the following summarizing table.

D. Winds at the Surface and Aloft. As previously explained, cold fronts may cause wind shifts up to 180° upon their passage. The wind shift at warm fronts may be of a much smaller magnitude. Winds aloft often give valuable indication of the intensity of



a. Clouds and Precipitation Associated with a Typical Frontal System Before Occlusion



b. Clouds Associated with Occluded Fronts

Fig. 93. Cloud shields associated with frontal systems.

surface disturbances as well as to the degree of overrunning.

E. Surface Temperatures. This has already been discussed and is included in the following summarizing table.

F. Humidity. The humidity may be estimated from comparison of dew point to temperature. Pseudo-adiabatic charts also give this information in terms of the actual mixing ratio. Humidity comparisons are particularly useful in conforming sites selected as frontal.

G. The following table has been compiled to summarize the previous discussion as to frontal characteristics as they are observable on the synoptic weather chart and other available supplementary data. (Fig. 94.)

Element		*Warm Front*	*Cold Front*	*Cold-type Occluded Front*
Clouds	A. Before the Front B. At the Front	Ci to Cs to As to Ns	Cs, As or Ac rapidly changing to Cb	As changing to Ns
	C. Behind the Front	Fs to Cu, or clear	FC or possibly St	Cu
Precipitation	A. Before the Front	None, then steady rain or snow	None, then heavy brief showers	Gradually increasing rain
	B. At the Front	Rain	Squalls or thunderstorms	Rain—brief
	C. Behind the Front	Clear or showers	Rapid clearing	Clearing
Pressure Tendencies	A. Before the Front	Falling	Falling	Falling slowly
	B. At the Front	Steady or falling less rapidly	Slight rise	Steady
	C. Behind the Front	Steady	Abrupt rapid rise	Rising slowly
Relative Humidity	A. Before the Front	Constant and then increasing	Fairly constant	Increasing
	B. At the Front	Near saturation	Increase near saturation	Steady
	C. Behind the Front	Decreasing from saturation to value higher than before the front	Rapid decrease	Decreasing
Specific Humidity	A. Before the Front	Steady	Constant	Increasing
	B. At the Front	Increase rapidly	Slight increase	Steady
	C. Behind the Front	Constant	Abrupt rapid decrease	Decreasing
Temperature	A. Before the Front	Steady—rising gradually as front is approached	Rising then falling slightly	Steady
	B. At the Front	Rising	Abrupt change	Steady
	C. Behind the Front	Steady—higher than in cold sector	Drops quickly	Slight fall
Visibility	A. Before the Front	Fair	Below normal	Becoming poor
	B. At the Front	Poor	Poor	Poor
	C. Behind the Front	Below normal—depends on air mass in warm sector	Good	Increasing to good
Surface Winds	A. Before the Front	S or SE	SW, S or W	S or SE
	B. At the Front	S, SE or SW	S or SW	W or NW
	C. Behind the Front	S or SW	NW, W or SW	N, NW or W

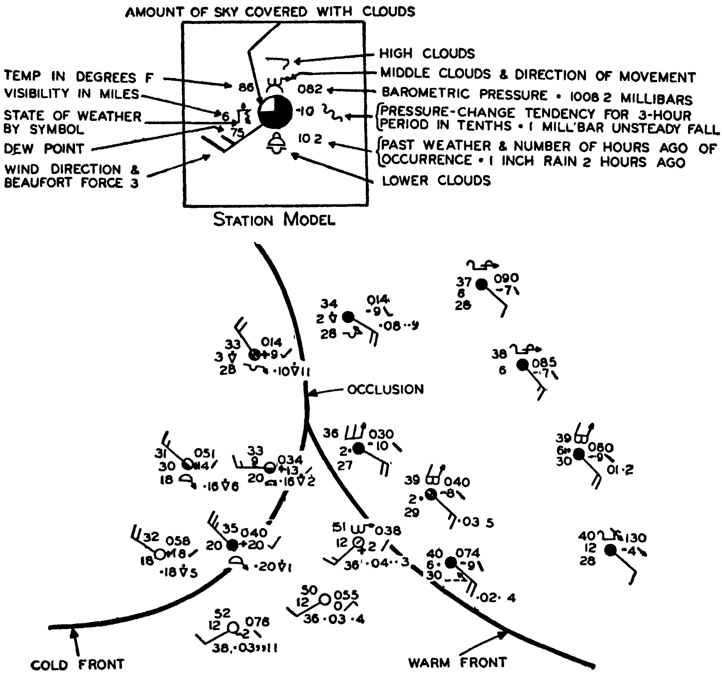


Fig. 94. Representative station entries as they appear on the synoptic chart associated with fronts.

TEST QUESTIONS ON TRAVELING DISTURBANCES AND FRONTS

1. The development of a transitory low-pressure area is known as (frontogenesis, cyclolysis, cyclogenesis, anticyclogenesis). 1. ________

2. The equatorial fiont is found in the (doldrums, horse latitudes, belt of prevailing westeilies). 2. ________

3. Arctic and polar air react along the (equatorial, arctic, polar) front. 3. ________

4. The average diameter of a traveling depression is (2000, 3000, 1000, 1500) miles. 4. ________

5. In (summer, winter) the polar front recedes toward the poles. 5. ________

6. Probably the most important primary front in North America is the (equatorial, arctic, polar) front. 6. ________

7. The warm sector is usually in the (northeast, northwest, southeast, west) quadrant of a low in the Northern Hemisphere. 7. ________

8. Wave formation along a primary front may be either ______ or ______. 8. ______

9. The pressure in a depression (increases, decreases) from the periphery toward the center. 9. ______

10. Monsoon lows are (frontal, orographic, nonfrontal). 10. ______

11. Occlusion of a frontal depression takes place after the wave has become (stable, unstable). 11. ______

12. The pressure in an anticyclone (increases, decreases) from the periphery toward the center. 12. ______

13. Orographic lows are (frontal, thermal, nonfrontal). 13. ______

14. The formation of active fronts is called (frontolysis, frontogenesis, katabatism). 14. ______

15. Subsidence is characteristic of (cols, highs, lows). 15. ______

16. The Azores High is a(n) (air mass, transitory, subsidence) high 16. ______

17. Low-temperature highs are (shallow, deep, average). 17. ______

18. Where the warm air overtakes and overruns the retreating cold air the (cold front, warm front, primary front) is found. 18. ______

19. When the cold air underruns warm air a (cold, warm, primary) front is formed. 19. ______

20. The appearance of an isallobaric low and converging winds along a primary front indicates (frontolysis, frontogenesis). 20. ______

21. A line connecting points of equal barometric tendency is (isobar, isallobar, isotherm). 21. ______

22. An approaching warm front is first indicated by the appearance of (stratus, nimbostratus, altostratus, cirrus, cirrostratus) clouds. 22. ______

23. Abrupt temperature changes occur with the passage of the (warm front, occlusion, cold front). 23. ______

24. Prefrontal, warm front thunderstorms may occur when the air in the warm sector is (stable, warm, cold, moist, dry, conditionally unstable). 24. ______

25. Stratified air in the warm sector will give rise to a (continuous, discontinuous, convective) prefrontal cloud deck. 25. ______

26. The wind discontinuity is greatest at the (warm front, cold front) 26. ______

27. The precipitation area is greatest at the (warm, cold, occluded) front. 27. ______

28. The squall head is identified with (a fast moving warm front, a slow moving cold front, a fast moving occluded front, a fast moving cold front). 28. ____________

29. The character and amount of precipitation is largely dependent on the characteristics of the air in the (cold sector, warm sector). 29. ____________

30. If the air in the warm sector is conditionally unstable, the approach of a cold front will be indicated by (cirrus, stratus, cirrocumulus, altostratus, altocumulus) clouds. 30. ____________

31. (Slow, rapidly moving) cold fronts often resemble warm fronts in their properties. 31. ____________

32. Cold fronts in low latitudes have (steep, moderate, gentle) slopes. 32. ____________

33. Subsidence in the rear of a rapidly moving cold front may cause the formation of (warm, occluded, secondary, primary) fronts. 33. ____________

34. There is a rapid decrease in relative humidity to the rear of a (cold, warm, occluded) front. 34. ____________

35. When cold air to the rear of a cold front overtakes cool air in advance of the warm front a (warm, cold) type occlusion results. 35. ____________

36. Upper air cold fronts are associated with (warm, cold) type occlusions. 36. ____________

37. (Warm, cold) type occlusions are characteristic of the Pacific Northwest. 37. ____________

38. (Warm, cold) type occlusions may be recognized by the appearance of an isallobaric discontinuity in advance of the surface occlusion. 38. ____________

39. Secondary cold fronts usually occur in (summer, fall, winter, spring). 39. ____________

40. After historical sequence the next most important criterion to follow in locating fronts on the synoptic chart is (wind-shift lines, temperature discontinuities, barometric tendencies, clouds and precipitation areas, humidity differences). 40. ____________

CHAPTER VIII

SPECIAL STORMS

I. THUNDERSTORMS

Probably the most spectacular of common storms is the thunderstorm. The awe-inspiring effects of thunder and lightning have influenced the course of men's lives, religion, and literature from earliest times. Zeus, Jupiter and Thor were identified by various peoples as the gods of the elements with the thunderbolt as their sign. In modern times thunderstorms represent a hazard to aviation and, as a result, they are objects of special study by meteorologists.

A. General Thunderstorm Characteristics. To be classified as a thunderstorm a storm must have audible thunder, visible lightning, or both. Usually a shower of rain or hail accompanies the storm. Thunderstorms occur in large cumulonimbus clouds, the tops of which have reached such a height that they consist of frozen particles and have a fibrous or feathery appearance (cirrus nothus). Such clouds may form when the air is conditionally unstable to at least two-miles' altitude and convection is initiated by mechanical or thermal means. In thermal thunderstorms when the air reaches the condensation level, it will rise unaided, resulting in strong vertical currents. Thunderstorms usually approach from the west or southwest. Hail, when it occurs, will be found in the front part of the storm. A squall cloud will mark the vortex between rising warm air and descending cold rain. Air mass thunderstorms are characteristic of cols and shallow depressions. (Figs. 95a and b)

1. The air entering a thunderstorm comes through the front undersurfaces. Since the area of cross section of ascending currents is very small compared to the area of the entire storm such rising currents attain velocities as high as 100 m.p.h. One of the most characteristic features of a thunderstorm is the wind gust preceding the general storm. Heavy rain falling from cumulonimbus clouds because of frictional drag cause a descending current of cold air preceding the cloud. This descending air is kept cool by evaporation of the rain although it is heated adiabatically because of descent. The evaporation tends to saturate the descending air. If the air becomes saturated it will be heated at the moist adiabatic rate as it descends. In its original ascent the air

cooled at dry adiabatic rate to a higher level. The result, then, in heating at the moist rate, is a steepening of the lapse rate as illustrated in the drawing. While this cold current has a descending movement in the direction of the storm, the ascending air has some motion in the opposite direction. Hence, an air-mass thunderstorm is preceded by two wind shifts, one in the front of the storm (the ascending air) and the other just as the storm breaks (the descending air).

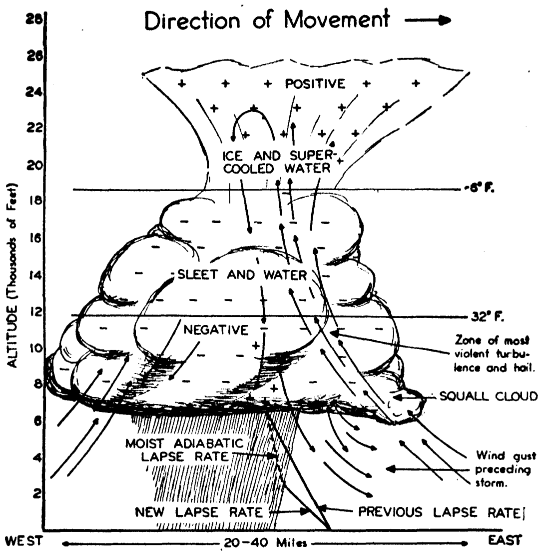


Fig. 95a. Structure of a typical cumulonimbus cloud.

← Direction of Movement

Fig. 95b. Photograph of a cumulonimbus cloud.

2. In thunderstorms of all types condensation occurs in the ascending air as soon as the temperature of this air has been reduced to its dew point. These drops of water may not immediately fall. If not they are carried upward by ascending air currents. Since small drops do not fall quickly they can be carried upward by relatively slight ascending currents. Large drops are unstable and are broken up by the turbulence within the cloud. If the ascending current is strong enough drops of water may be forced high enough to freeze. The frozen pellets may then enter a descending current and be returned to the zone where liquid water can be picked up on their surfaces. Frozen particles with liquid coatings may be forced aloft again and again until they become too heavy for the ascending current and fall as hail. Due to this cumulative method of formation, hailstones are composed of many layers, similar to the structure of an onion.)
3. Due to the fact that the strongest vertical currents are in the forepart of the cloud, thunderstorms characteristically have large raindrops first with the size decreasing toward the end. The frequent renewal of heavy drops during the storm is a phenomenon peculiar to thunderstorms. Since a great amount of water is held within the thunderstorm cloud, when the vertical currents are in some way interfered with, "cloudbursts" may result. (A "cloudburst" is merely a sudden downpouring of most of the available water which is being held aloft in a cumulonimbus cloud by vertical currents.)
4. In all of the main essentials a thunderstorm is the same as a convective shower except for the electrical phenomena associated with the former. At all times strong electrical potentials are found between the upper air and the surface of the earth, as well as between the various air layers. The air in which thunderstorms are developing often has weaker natural electrical potentials than in times when no thunderstorm activity is generating. Of course, when the thunderstorm has actually developed the electrical potentials are very high, but the point is that the great electrical potentials must have been generated in some other manner than the normal method of generation of atmospheric electricity. Simpson has suggested that the generation of thunderstorm electricity is due to the disruption of raindrops. This theory maintains that large raindrops are disrupted by the violent vertical currents inherent to the storm. The large drops maintain a positive charge. whereas the small drops are negative. Due

to the violent convective currents set up in a thunderstorm, charges of positive and negative electricity accumulate in different parts of the cloud. When the potential difference becomes great enough the insulating effect of the air is broken down and a discharge of lightning occurs. The intense heating in the path of a lightning flash causes the air to expand with near explosive violence. As a result, sound waves are generated which are recognized as thunder. Thunder rumbles because of the varying distances of the generating lightning flash from the observer and is also due to the reflection of the sound waves from hills, mountains or other obstacles. Lightning occurring below the horizon appears as flash or heat lightning when it is reflected from the upper cloud decks.

B. Frequency of Occurrence of Thunderstorms.

1. Over the Ocean. Since the temperature of the ocean varies only slightly, and in comparison the air temperature varies a great deal more, the most favorable time for convection over the ocean occurs between midnight and 4 a.m. At that time the upper air at an altitude of 1500 ft. to 3000 ft. has undergone its maximum cooling. As a result those temperature gradients most favorable for rapid vertical convection are most frequent during the early morning hours.

2. Over the Land. When the surface is most heated the maximum convection occurs. Over the land this period occurs in the afternoons from 2 to 4 p.m.

3. Yearly Periods. Over the oceans the conditions most favorable for thunderstorms occur during the winter. Over the land the reverse is true and the period of maximum occurrence is during the summer.

C. Classification of Thunderstorms. The prime requisites for thunderstorms are instability, high temperatures and high humidities. The severity of a thunderstorm is directly dependent upon these factors. Instability sufficient for the generation of a thunderstorm may be brought about by surface heating, orographic lifting, overrunning of warm air by cold currents aloft, or lifting along a frontal surface. Thunderstorms that occur within a relatively dry air mass are usually dry thunderstorms and lacking in severity. Since the characteristics of all thunderstorms are similar, and because their main differences are due to the manner in which they are set off, they are often classified in the following manner. Air-mass thunderstorms include "heat" or thermal thunderstorms and thunderstorms caused by overflowing of cold currents aloft. Frontal thunderstorms include the cold-

front type, warm-front type and the occluded-front type.) (Fig. 96)

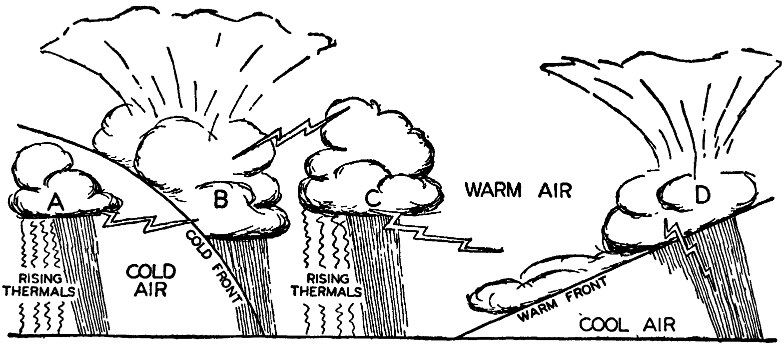


Fig. 96. Thunderstorm types.

A—Air-mass thunderstorm due to convective instability and overrunning by cold air aloft. B and D—Frontal thunderstorms due to lifting of moist air along a frontal surface. C—Air-mass thunderstorm due to heating and instability.

1. Air-mass Thunderstorms. In general, air-mass thunderstorms are of two types. Air-mass thunderstorms may be due to local convection in a warm air mass or they may be found within thermodynamically cold air masses. Local convection thunderstorms are also known as "heat" thunderstorms. They occur most often over land on heated afternoons when the humidity is high. The other type of air-mass thunderstorm is caused by cold air currents aloft which produce the necessary steep temperature gradient and resultant instability to produce mild thunderstorms. Air-mass thunderstorms are not associated with any definite isobaric formation.

   a. The mechanics of these storms are such that they repel one another, and when formed they do not occur close together. The pilot may usually alter his course to fly between or around such storms. Caution should be observed in this respect since, if the storms are relatively close together, the vertical currents between them may be violent. Air-mass thunderstorms usually form in the afternoon, travel with the prevailing wind, and die out in the late afternoon. In some cases these storms will continue late into the night if an adequate supply of warm, moisture-laden air is available.

   b. No frontal activity is necessary for the formation of air-mass thunderstorms. Characteristically, most air-

mass thunderstorms occur in Tropical Maritime air in summer. The Tropical Maritime air should be at least two and one-half miles deep for thunderstorms of the air-mass thermal type to develop. As Tropical Maritime air departs farther and farther from its source region, continued precipitation from convective activity reduces the moisture content. Because of this tendency, Tropical Gulf air, in the northern part of its trajectory, will often develop thunderstorm activity only when it is lifted over the Appalachian Mountains. Thunderstorms resulting from such orographic lifting may be nearly stationary.

c. When thunderstorms occur in cold air masses they are usually due to the overrunning of a warm surface by cold Polar Continental air. Such overrunning results in steep lapse rates in the lower layers. The usual result of this activity is merely instability showers. However, in the spring and early summer such instability showers may develop into mild thunderstorms. Strong thunderstorms will not occur under the above conditions because in the cold air the required humidity is lacking.

2. Frontal Thunderstorms. In general characteristics air-mass and frontal thunderstorms resemble each other. There is the difference, however, that frontal thunderstorms need not necessarily occur at the time of maximum thermal convection although surface heating may serve as an additional cause for their formation. Frontal-type thunderstorms are due to mechanical convection along the frontal surface; hence, they may occur over the land at night and over the sea during the day. Thunderstorms of the frontal type are more often associated with cold fronts than warm fronts since at the cold front both the thermal discontinuity is more marked and the frontal surface is steeper. When convective conditions become such that thunderstorms occur simultaneously all along a cold front the condition is known as a *line squall.* When such conditions prevail it is obvious that the flyer will usually be unable to fly around them. The safest course is to land at the nearest alternate airport until the storms have passed over.

D. Forecasting of Thunderstorms. An intimate knowledge of the air masses involved is a prime requisite to the thunderstorm forecaster. The effect of diurnal heating must be estimated. Local forecasting of clouds is also useful. The presence of altocumulus castellatus in the morning indicates the convective activ-

ity that may produce a thunderstorm in the afternoon. Growing cumulus in mountainous regions may develop into cumulonimbus. The exact time and occurrence of a thunderstorm is very difficult to forecast. In the case of frontal thunderstorms, the conditions along the front will determine the possibilities of thunderstorm occurrences.

1. The pseudo-adiabatic chart may be used to great advantage in forecasting the possibility of air-mass thunderstorms of the thermal type. This energy chart should be used in conjunction with the synoptic surface map if satisfactory results are to be expected. Obviously, a frontal passage, bringing with it a new air mass, will nullify any forecasts that may have been made on the basis of upper-air soundings within the prefrontal air mass. In forecasting from the energy diagram, then, the first step is to make sure that a frontal passage will not occur during the time of the forecast. The general characteristics of the prevailing air mass should next be examined. These physical characteristics become apparent when the positive and negative areas for thermal lifting are plotted as previously described in Chapter IV. If the pseudo-adiabatic chart has been prepared from an early morning sounding, and the sky is clear, there will probably be adequate time for sufficient surface heating to bring about convection from the surface, providing other conditions are favorable. Negative energy areas must be given more weight in considering the thunderstorm possibilities than the positive areas because the negative areas prevent convection. Again, in studying tephigrams for the purpose of forecasting thunderstorms it is important to observe the changes in positive and negative areas chronologically. When several soundings are available during the day, increasing positive areas and decreasing negative areas are highly favorable indications of possible thunderstorm activity. To forecast a thunderstorm with some assurance the positive energy areas should be at least twice as great in area as the negative areas. In addition the positive area should extend to a sufficient altitude to be beyond the zero isotherm. This final condition insures glaciation and the development of cirrus nothus, a requirement for active thunderstorms. If the temperature necessary for the thermal convection seems unlikely of attainment under prevailing conditions a thermal thunderstorm should not be forecast even though other circumstances may be favorable. For example, if the sounding was not taken until late in the morning and considerable surface heating was still required

to overcome surface stability, then a decision must be made as to the possibility of sufficient heating in the time remaining to bring about convection from the surface. Since the diurnal temperature range is reduced by cloud coverings, a thunderstorm would not be forecast under the same conditions as seen on the chart on a clear day as on an overcast day. On some occasions very dry air masses such as Tropical Superior may overrun moist layers of Tropical Maritime origin. Under such circumstances, positive and negative areas plotted on the basis of a particle of the underlying air mass may give false indications as to thunderstorm probability. To prevent an inaccurate forecast in such an eventuality, the depegraph should be examined and any marked decrease in relative humidity aloft will indicate the above possibility. In such a case a thunderstorm should not be forecast.

2. Under certain conditions, while the surface heating may be insufficient to bring about thermal thunderstorms, frontal or orographic lifting may be able to provide the requisite trigger action to bring about the occurrence of the frontal or orographic types. To forecast this possibility the procedure outlined in Chapter IV for plotting positive and negative energy areas for mechanical convection is followed. It must be kept in mind that if the sounding was taken in the early morning there may be sufficient surface heating to hasten the orographic or frontal lifting action so that thunderstorms will occur at a lower altitude and, in the case of frontal types, at an earlier time than would be forecast by referring solely to the chart. This circumstance may be allowed for by estimating the temperature at the time of the frontal approach. Energy diagram methods may be used to make this estimate. The new temperature is then used to plot the energy areas for mechanical lifting. The previous criterion for judging energy areas is finally applied and the forecast made.

3. When an examination of the surface synoptic map shows that a frontal passage will occur, the possibility of thunderstorms in the postfrontal air mass should be considered. All of the foregoing methods should be applied to a sounding taken at some station already within the air mass being studied. In addition, the forecaster must make allowance for possible latitudinal differences or the complications of local conditions. For example, at some stations thunderstorms may be prevented or delayed by the advent of a sea breeze.

4. If upper-air soundings are not available to forecasters they may make use of certain indications on the surface synoptic chart. Areas of converging wind in the warm sector of extratropical cyclones are watched for the appearance of thunderstorms. Thunderstorms often occur in Tropical Maritime in summer, associated with the rapidly falling pressure in advance of a cold front. Thunderstorms of this type are known as *prefrontal.* Warm-type occlusions may give rise to thunderstorms if the air being occluded from the warm sector has the required physical characteristics. (Fig. 97) Any thunderstorms occurring under the conditions of

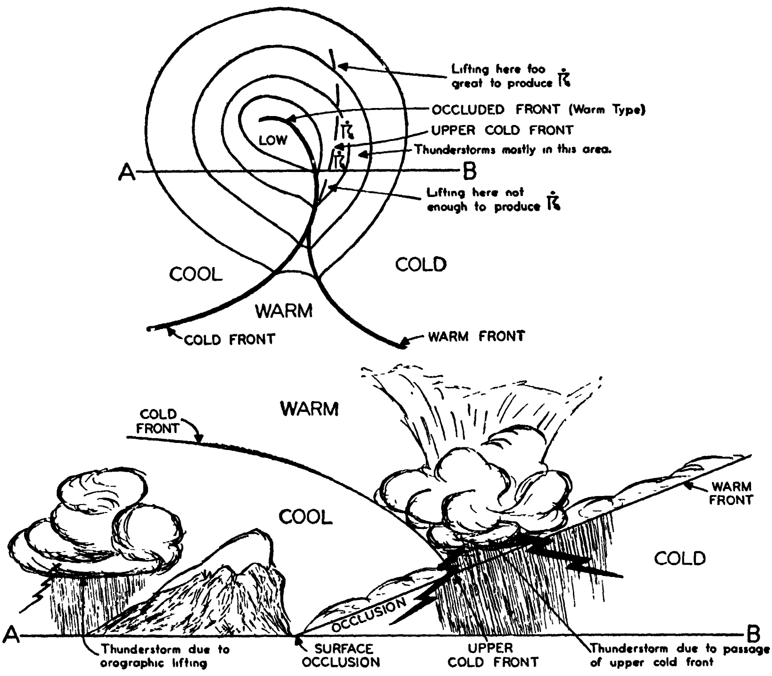


Fig. 97. The upper cold front thunderstorm.

the warm-type occlusion are found in a rather limited area near a section of the "upper air cold front." At the top of the warm sector, occlusion is just beginning to take place. As a result the warm-sector air may not have been lifted sufficiently to produce instability. Toward the outer end of the occlusion the lifting process has already desiccated the air. Hence, if thunderstorms are to occur in connection with the occlusion they will be found near the area indicated

in Fig. 97. The movement of air-mass thunderstorms may be very difficult to anticipate. Once they have been generated their movement may be followed with some success by reference to teletype reports. If data on the upper winds are available the movement of an air-mass, thermal-type thunderstorm may be prognosticated to some degree by the direction of the winds at 10,000 ft. Since the conditions for thunderstorms of this type are most favorable when the pressure gradient is slight and the winds light or variable their movements are often erratic. Heat thunderstorms may follow the most available supply of humid air. If warm, moist air is continually available a thermal-type thunderstorm may maintain itself for as long as 12 hours. In certain synoptic situations, when the wind direction changes considerably with height, the upper air may have a very different origin from that of the surface layers. If cold air flows in aloft over warmer surface air, steep enough lapse rates may result to cause mild thunderstorms.

E. Flying Conditions in Thunderstorms. Unless an aircraft is able to climb quickly to at least 15,000 ft. it is extremely unwise to attempt to fly over a thunderstorm. Even at this altitude the top of the storm will not be reached, although probably the most violent vertical currents will be avoided. Cumulonimbus clouds may extend to altitudes of 30,000 ft. or more. Again, the time and fuel consumed in trying to climb over a thunderstorm makes the procedure impractical. Of course, it is extremely hazardous to attempt to fly through a thunderstorm at ordinary flight altitudes since the violent, vertical currents impose structural strains on the craft as it flys from updrafts to downdrafts or through currents of varying velocities. In addition to the hazards of excessive turbulence, severe icing conditions may be encountered in cumulonimbus clouds. Reduced visibility makes contact flying (flight by reference to visible landmarks) impossible and the static caused by lightning discharges renders blind-flying methods untrustworthy. Air-mass thunderstorms may be avoided by flying around them. If two or more such thunderstorms occur close together it is unwise to try to fly between them as the currents between the storms may be very strong. However, it is usually the better procedure to attempt to fly between thunderstorms than to attempt to fly under them. (The downpour of rain usually associated with the storm and the general lowering of the cloud deck restricts the visibility, static disrupts radio communication, and downdrafts may force the aircraft to a dangerously low altitude. Although lightning represents one of the most important and awe-inspiring attributes of the thunderstorm

to the uninitiated, it is probably one of the least of the storm's flight hazards. The energy used in any electrical circuit is equal to $I^2 \times R$. In an aircraft high resistance may cause destruction of parts. If an aircraft is thoroughly and effectively bonded (all parts connected so as to complete a continuous electrical circuit) little damage should result even when the craft is directly in the path of a lightning discharge. The resistance of a wire or small part varies inversely as the cross-sectional area. Hence, radio antennas should be drawn into the plane when electrical storms are encountered in flight, as their high resistance, due to small cross-sectional area, will cause them to be destroyed by the great quantities of electrical energy available in lightning discharges. Objects and personnel in the interior of an all-metal aircraft are protected from lightning by the "Faraday" cage effect. Faraday found in his experiments that even delicate electroscopes were unaffected by electrical discharges occurring on the surface of metal covers surrounding them. About the only real damage that has been definitely traced to lightning has been holes punctured in the tail surfaces or ailerons where the bonding was evidently imperfect. Radio equipment and aerials have been damaged when the aerials were left exposed. In some cases freak accidents have been attributed to lightning. In one instance a heavily loaded plane flew into an orographic thunderstorm in attempting to clear a mountain range. Downdrafts were forcing the plane downward so that it became evident that the mountain directly ahead could not be cleared. To lighten the airplane the pilot dumped the wing gas tanks at the same instant that a lightning flash occurred. The flash ignited the gasoline and destroyed the plane. Such accidents are, of course, fortunately very rare and lightning usually represents a minor hazard to aviation. Thunderstorms occurring in advance of the warm front may be flown into by pilots flying blind through the lower stratus layers while making cross-country transport flights. However, the efficient meteorological services of commercial airways, as well as the Government services, usually prevent this eventuality by forecasting the possibility and rerouting the flight.

II. LINE SQUALLS

The line squall occurs along the wind-shift line of a "V" depression at a rapidly moving cold front. The line squall extends along a line which may be several hundred miles long, orientated usually in a north-south direction. In most cases it is accompanied by rain or hail. A pronounced shift of wind characterizes the storm. Inasmuch as the line squall is strictly a phenomenon of the cold front, the air behind the storm is colder than that preceding it. The clearing of the storm

condition is quite rapid when viewed from an observing station as the front travels rapidly. The passage of the storm brings a veer in the general wind direction. A low roll cloud extending all along the front is characteristic of the line squall. The winds in and near this squall cloud are often of much greater speed than the prevailing wind. Line squalls are accompanied by violent convective conditions, large towering cumulus or cumulonimbus clouds, heavy rain of short duration, perhaps with hail or thunder. Such line squalls may be masked at low altitudes by low stratus-type clouds. Except where cumulonimbus clouds have developed to high altitudes the line squall does not itself extend to extremely high altitudes.

III. THE TORNADO

Strong convective activity and marked thermal discontinuity bring about the most violent and most sharply defined of all storms, the tornado. While tornadoes may be found in other parts of the world between the latitude limits 20° to 40°, they are uncommon except in the central and southeastern portions of the United States.

A. General Characteristics. The tornado is one of the most violent, yet least extensive, of all storms. It consists of a funnel-shaped, circular column of upward spiraling winds of destructive velocities. The extent of the destructive part of the storm averages about 1000 ft. in diameter. The horizontal speed over the surface of these storms varies between 25 to 45 m.p.h. The

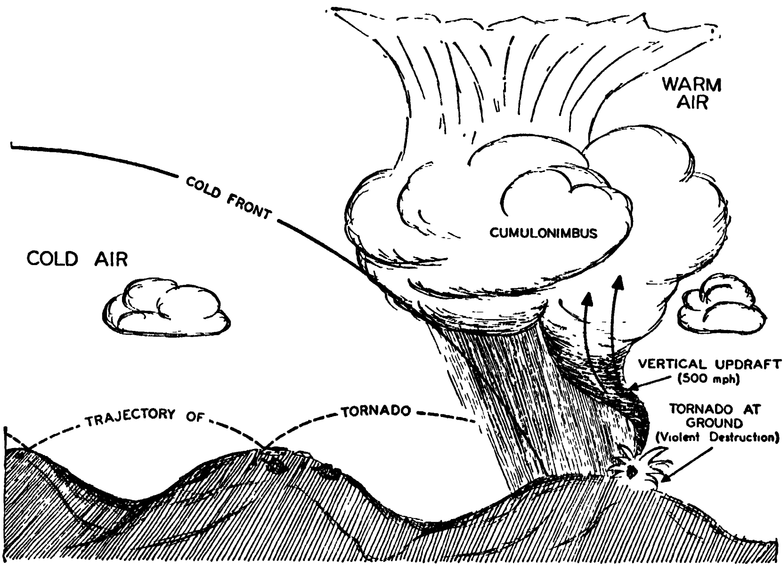


Fig. 98. The tornado.

length of their path over the ground is usually from 20 to 40 miles although at times they may leave a path of destruction for 300 miles. Tornadoes travel northeastward in the Northern Hemisphere. Hence, when they are visible during the day they may be avoided by aircraft, in most cases, by turning southward. (Fig. 98)

B. Origin. Tornadoes occur along abrupt cold fronts of strongly contrasting air masses. They are found mainly in spring or early summer and usually from two to five in the afternoon at the time of maximum surface heating. They may continue their activity well into the night. Tornadoes occur in central United States in the spring and early summer when Polar Canadian and Tropical Gulf or Tropical Atlantic air meet. When tornadoes originate over the sea they are called waterspouts. Waterspouts are, in most cases, less violent than the tornado. While the more violent type of waterspout, like the tornado, appears first in the cloud and then extends down to the sea surface, some rather minor waterspouts have been reported as originating at the sea surface on clear days. This type is believed to be a phenomenon similar to dust devils and whirlwinds over the land. This latter type is characteristic of the Gulf of Mexico.

IV. TROPICAL CYCLONES

The most destructive of storms, the tropical cyclone, occurs in many parts of the world. It is known by various names. In the western North Pacific it is a typhoon; in the Bay of Bengal and the north Indian Ocean, a cyclone; in Australia, a willy-willy; in the Philippines, a baguio; while in the South Pacific, east North Pacific, south Indian Ocean, North Atlantic, Gulf of Mexico and the Caribbean Sea the tropical cyclone is known as the hurricane. Tropical cyclones consist of a vast whirl of rapidly moving air currents circulating with indescribable fury around a center of very low pressure. The diameter of such storms varies from 300 to 600 miles. (Fig. 99)

A. Origin. Tropical cyclones occur over the warmer portions of most of the oceans. Their most characteristic place of origin is in the doldrums, 10° to 20° from the equator. Most of them occur during summer or autumn. It is believed that they are of convective origin. Briefly, the theory is that when heating takes place over a relatively large area simultaneously the air over the area is displaced by colder air from the sides and above. Once this process is started, the release of latent heat from condensation, the heating of the ascending current due to selective absorption, and the rotation of the earth all contribute to the birth and maintenance of the tropical cyclone. Hence, in summary, it may be said that the two major contributing factors are warm,

tropical, saturated air of the oceans and overlying, cool air in the upper atmosphere. The energy for continuation of such storms is furnished by condensation. Thus, when they move inland they may soon dissipate to become only moderate storms.

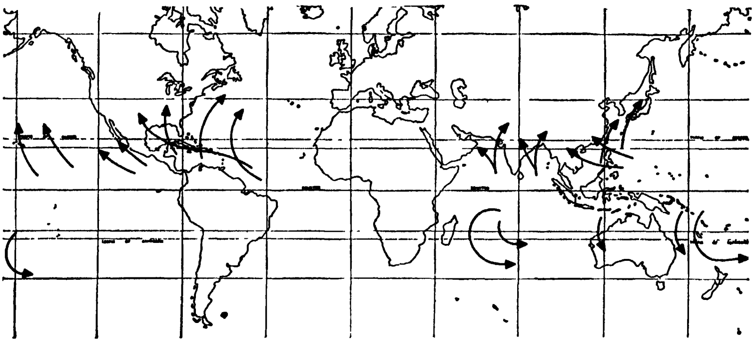


Fig. 99. Source regions of tropical cyclones and their characteristic paths.

B. General Characteristics.

1. Winds. In the Northern Hemisphere the winds in a tropical cyclone have a counterclockwise motion. At the outer limits of the storm the winds are light to moderate, and gusty. As the center is approached the winds increase to furious gales and, finally, to a full hurricane whose violence continues to increase until the central vortex is reached. The winds in the hurricane are believed to be often as great as 250 m.p.h. A wind of 231 m.p.h. has been recorded.
2. The Calm Center. The calm center or "eye" of the tropical cyclone varies between 6 to 30 miles in diameter with the average diameter being 14 miles. Whereas the rest of the storm is violent, the "eye" is calm with only light variable winds, if any, and often a clear sky and sunshine. The lowest pressures, highest temperatures, and lowest relative humidities are found in this zone. At sea the highest seas may occur in the calm center. The lowest pressure ever recorded in a storm center was 26.185 in. (886.63 mb) on August 18, 1927, by the Dutch steamship *Sapoeroea,* off the coast of Luzon, P. I. (Fig. 100)
3. Tidal Effects. Tidal waves may be associated with tropical cyclones when the slope of the ocean bed and the contour of the coast line are favorable. In the Northern Hemisphere the most disastrous tidal waves occur where there is a gently sloping ocean bed and a bay to the right of the

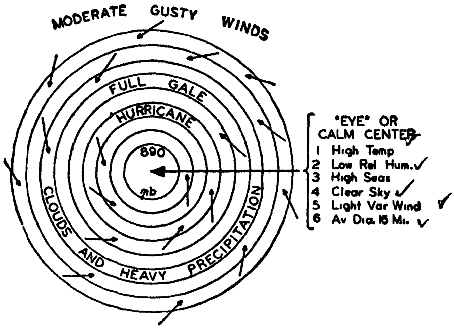


Fig. 100. Characteristics of the Northern Hemisphere tropical cyclone.

path of motion of the storm. Waves generated by the storm outstrip the forward motion of the tropical cyclone and the *storm swell* is often taken as a sign of the approach of a hurricane by natives of hurricane areas. (Fig. 101)

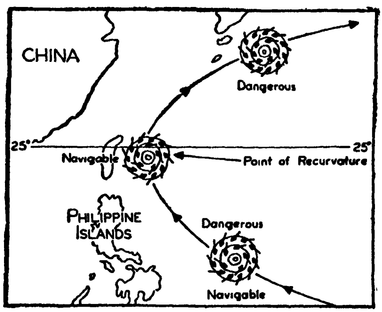


Fig. 101. Trajectory of a tropical cyclone in the Northern Hemisphere.

4. Movement. Tropical cyclones recurve at latitudes ranging from 25° to 30° north or south depending on the time of year. At the time of recurve hurricanes move at their slowest speed especially if the change of direction is abrupt. The average 24-hour movement is 260 miles before recurve and 392 miles after the recurve. In the Northern Hemisphere the usual movement is toward the northwest changing to north and, finally, to northeast. When a tropical cyclone is blocked by an anticyclone it will move southwestward or westward and then resume its movement to the northeastward after being freed from the influence of the anticyclone. In certain unusual cases tropical cyclones in

the Northern Hemisphere have been known to describe loops to the left of their path of motion. The West Indian cyclone of October 1910 described such a loop over the northwestern coast of Cuba when it came under the influence of a high-pressure area lying over the United States.

TEST QUESTIONS ON SPECIAL STORMS

1. Thunderstorms occur in (cirrus, altocumulus, altostratus, cumulonimbus, nimbostratus) clouds. 1. ________

2. The glaciation at the crest of the thunderstorm cloud is (cirrocumulus, cirrostratus, cirrus fumulus, cirrostratus nebulosus, cirrus nothus). 2. ________

3. For thunderstorms to occur an air mass should be conditionally unstable for at least (1, 2, 4, 5) miles' altitude. 3. ________

4. The gust immediately preceding a thunderstorm is due to (heating, mechanical, convectional, frictional) effects on the air. 4. ________

5. Air-mass thunderstorms are characteristic of (deep lows, strong highs, cols or shallow depressions, moderate highs or lows). 5. ________

6. As the air descends from the thunderstorm cloud it becomes saturated. Because the air ~~is then~~ heated at the moist adiabatic rate the lapse rate is (decreased, increased). 6. ________

7. Hailstones ha~~ve a~~ (concentric leaf-like, hollow spherical, porous) structure. 7. ________

8. Large drops descend from the (fore, middle, rear) part of the thunderstorm cloud. 8. ________

9. When the ascending cloud currents in a thun~~derstorm are~~ suddenly stopped (waterspouts, tornadoes, hurricanes, cloudbursts, willy-willys) occur. 9. ________

10. Often the air in which a thunderstorm is soon to develop will have (a) (weaker, the same, stronger) potential (than (as) the ordinary electrical ~~potent~~ial. 10. ________

11. According to Simpson, thunderstorm electricity is due ~~to (heating, cooling,~~ friction between the cloud and the air, downdrafts, disruption of raindrops). 11. ________

12. ~~The upper~~ portions of the thunderstorm cloud are (positively, neutrally, negatively) charged. 12. ________

13. The three prime requisites ~~for~~ the generation of thunderstorms are: 13. ________

14. Air-mass thunderstorms are of (1, 2, 3, 4, 5) main types. 14. ________

15. Air-mass thunderstorms (attract, repel, are neutral to) one another. 15. ________

16. Air-mass thunderstorms over the land usually form (at night, in the morning, in the afternoon, during the evening). 16. ________

17. Air-mass thunderstorms caused by the overflowing of cold air aloft are in most cases (mild, strong, moderate) storms. 17. ________

18. Most air-mass thunderstorms occur in (Tropical Continental, Polar Continental, Polar Maritime, Tropical Maritime) air in summer. 18. ________

19. Tropical Gulf air in the northern part of its trajectory in summer requires (subsidence, high winds, mechanical lifting, surface cooling) to cause the formation of thunderstorms. 19. ________

20. Frontal thunderstorms are more common along (cold, warm, occluded) fronts. 20. ________

21. In forecasting air-mass thunderstorms the possibility of pp 160 must first be considered. 21. ________

22. To forecast air-mass thunderstorms by using the pseudo-adiabatic chart the technique for (thermal, mechanical) lifting should first be employed. 22. ________

23. In weighing the thunderstorm possibilities it is necessary to remember that before convection will occur (positive, negative) energy areas must be obliterated. 23. ________

24. If a thunderstorm is to occur the top of the positive energy area should extend to or beyond the [illegible] 24. ________

25. If a sounding is taken late in the morning and an inversion still persists there is (less, the same, more) chance for a thunderstorm to occur than if this condition were shown on an early morning sounding. 25. ________

26. Conditions are (more favorable, less favorable, the same) for air-mass thunderstorms when the sky is overcast than when the sky is clear. 26. ________

27. A rapid decrease in relative humidity aloft indicates (favorable, unfavorable, neutral) conditions for thunderstorm occurrence. 27. ________

28. To forecast the possibility of orographic-type thunderstorms by the use of the pseudo-adiabatic chart the technique for (thermal, mechanical) lifting should be employed. 28. ________

29. Surface heating may (hasten, retard, not influence) the formation of orographic or frontal thunderstorms. 29. ________

30. When a frontal passage is imminent pseudo-adiabatic analysis should be applied to the air mass (preceding, following) the front. 30. ________

31. Thunderstorms associated with an upper cold front will occur (at the juncture of warm and cold fronts, near the middle of the occlusion, at the outer end of the occlusion). 31. ________

32. Thunderstorms of the air-mass type will move with the wind at (1000, 2000, 4000, 8000, 10,000, 15,000) ft. 32. ________

33. The major hazard to aircraft caught in thunderstorms is (lightning, violent air currents, icing, reduced visibility.) 33. ________

34. Areas of high electrical resistance are (most, neutrally, least) likely to be damaged by lightning. 34. ________

35. Line squalls occur at (rapidly, moderately, slowly) moving cold fronts. 35. ________

36. Tornadoes occur most characteristically associated with abrupt (warm, cold, occluded) fronts. 36. ________

37. The highest temperature in a tropical cyclone is found in the (southwest sector, southeast sector, northwest sector, the calm center, the outer portion). 37. ________

38. Tropical cyclones usually originate in latitudes (0° to 10°, 10° to 20°, 20° to 30°, 30° to 40°). 38. ________

39. Hurricanes recurve in latitudes (5° to 10°, 10° to 15°, 15° to 20°, 20° to 25°, 25° to 30°). 39. ________

40. The rotation of the willy-willy is (clockwise, counterclockwise). 40. ________

CHAPTER IX

FOGS AND ICING CONDITIONS

I. CLASSIFICATION OF FOG

Fog consists of saturated air containing considerable condensed vapor. When the horizontal visibility is reduced to 1100 yd. or less due to the presence of water particles in the air, the phenomenon is identified as fog. Fogs have been classified according to many different criteria. In some cases, fogs are named after the localities where they occur. Thus, there are California fogs, Grand Banks fogs, and Arctic fogs. Again, fogs have been identified with other meteorological processes so that there are land- and sea-breeze fogs and monsoon fogs. Probably the most logical method of fog classification for scientific purposes is the classification on the basis of fog-producing processes. The basic physical processes leading to fog formation are evaporation, adiabatic and nonadiabatic cooling. In the following outline the more common and less general fog types will be subclassified under the class of fog-producing process which leads to their formation.

II. FOG TYPES

A. Fogs due to Evaporation. In meteorology, vapor pressure refers exclusively to the pressure exerted by water vapor. Molecules of water vapor exert a pressure as they escape from the surface of the free liquid. After escaping into the air they exert a pressure which is proportional to the number of them present. Since the amount of water vapor that can be contained in a given volume of air increases with the air temperature, the vapor pressure also becomes greater at higher temperatures. The tendency for molecules to escape from a liquid increases with a rise in the temperature of the liquid. Thus, the vaporization tendency is from warm liquids into cold air. This process will continue after the air has become saturated if the vapor pressure of the saturated cold air is less than the vapor pressure of the warm liquid, and fogs will be formed. When the air above a liquid has a higher temperature than the water surface over which it lies, fog cannot be produced by evaporation processes.

1. Rain-area and Frontal Fog. Along both the warm and cold fronts, warm air is being lifted over the discontinuity surface above the cold air beneath. When precipitation takes place, the raindrops formed will be warmer than the air through

which they must fall in order to reach the ground. Inasmuch as the precipitated water droplets are warmer than the air through which they are falling, evaporation will take place from the falling moisture into the cold unsaturated air. The cold air becomes saturated quickly but the evaporation process continues. The moisture, evaporated after saturation has taken place, immediately condenses thus forming visible water particles or cloud. If this process is progressive and turbulence is at a minimum, the cloud deck will build down to the ground level and fog will be the result.

a. Prefrontal (Warm-front) Fog. When the air in advance of a warm front is stable, and the winds are not too strong, an evaporation fog may be formed in the manner just described. If the air is unstable, or strong winds cause considerable turbulence, the same effect may cause stratiform clouds to develop under the original cloud layer formed along the discontinuity surface. Prefrontal fog of this type is probable when Tropical Maritime air overruns Polar Continental air in advance of a slowly moving warm front.

b. Postfrontal (Cold-front) Fog. Postfrontal fog requires the same conditions for its formation as prefrontal (warm-front) fog. Extensive areas of postfrontal fog only occur, however, when the cold front has become quasi-stationary. (Unstable air masses following cold fronts have cumuliform clouds associated with them rather than fog.)

c. Evaporation-occlusion Fog. Since occlusions partake of the characteristics of both warm and cold fronts, evaporation fogs may be found associated with them under the conditions described for prefrontal warm-front and postfrontal cold-front fogs.

d. Rain-area Fog. When, for any reason, warm precipitation falls through a cold, stable layer of air, evaporation fog may be formed.

2. Steam Fogs. When cold, stable air overflows a water surface several degrees warmer than itself, steam fogs are formed. Since vapor pressures are proportional to the temperature, a vapor-pressure gradient exists between the warm water surface and the overlying air. When strong inversions are present, such as might be expected in stable air, the upward transport by convection or turbulence is minimized. As a result, a relatively closed system is maintained near the water surface. If, when saturated, the vapor pressure of the air is still less than the vapor pressure of the water, then,

as excess vaporization takes place from the water, condensation will occur in the overlying air. This results in visible moisture (steam fog) near the surface. In order for the "steam" to concentrate sufficiently to form fog, there must be strong pre-existing inversions and very light winds. On clear nights, steam fog may form over inland lakes and rivers in late fall before they are frozen. Such lake and river steam fogs are especially prevalent along the Mississippi and Ohio rivers at that time of year. In regions where ice and open water coexist, conditions for the formation of steam fog are particularly propitious because the ice cools the air that comes in contact with it, which, in turn, flows out over the warmer water causing steam fog. Hence, in arctic regions, steam fogs have been named "arctic sea smoke." Extreme differences in temperature between the sea and the air are favorable to the formation of steam fogs. Instability, or strong winds, would distribute the condensed moisture through too great a layer to permit it to concentrate sufficiently to result in fog. (Fig. 102)

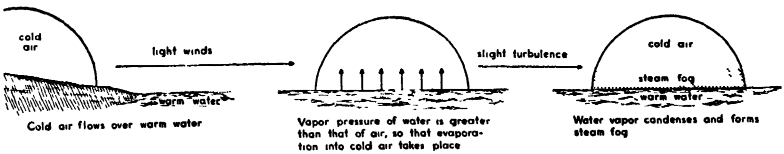


Fig. 102. Steam fog.

B. Fogs due to Adiabatic Processes. Air, upon rising, cools adiabatically. If the air has a high relative humidity very little upward displacement may bring about condensation. The convergence of nearly saturated air, adjacent to slowly moving fronts may thus bring about the formation of fog due to adiabatic cooling. Again, if air is forced to rise mechanically along a sloping surface, condensation may occur in a similar manner.

1. Convergent Fog. Fog of this general type may be either prefrontal or postfrontal since it may occur wherever the air, near a front, is forced to ascend by convergence. It may be associated with warm fronts, cold fronts or occlusions. Unless the air adjacent to the front has a very high relative humidity stratus clouds are more probable than fog. However, when stratus clouds do form they occur at a very low level and represent nearly as great a hazard to aviation as actual surface fog. A difference between the dew-point temperature and the air temperature of only one degree

Centigrade will result in the formation of stratus clouds at about 500 ft. In some cases, the air is so near saturation at the surface front that the degree of lifting necessary to produce fog is negligible. The area of convergent fog and low stratus formation is much broader in advance of the warm front than in the rear of the cold front due to the difference in the degree of slope of the discontinuity surfaces. Convergence may be aided by other processes, such as evaporation and radiational cooling, in producing fog.

2. Upslope Fog. In regions where there is a gradual upslope of the terrain, fogs are often formed as a result of adiabatic cooling. Moderate winds will accelerate the formation of upslope fog since the more rapid ascent will tend to neutralize the effects of turbulent mixing, thus preventing the transportation of heated air from the surface upward and neutralizing the adiabatic cooling effect. If the winds become too strong, however, only stratus clouds will be formed. Upslope fog may be dissipated by blowing out over very dry country. Stable stratification of the air and high humidity are favorable for the formation of upslope fog. Since upslope fogs are formed within ascending currents of air along natural rising topography, they are usually deep fogs extending through the entire moving layer. (Fig. 103)

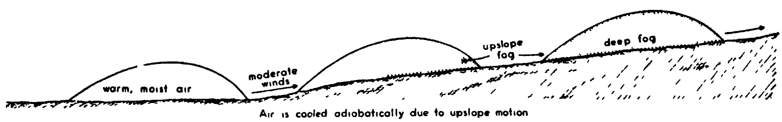


Fig. 103. Upslope fog.

3. Isobaric and Isallobaric Fogs. Two theoretical fog-producing influences are found, one in the flow of the air across the isobars toward lower pressure at the surface in a low, and the other in the gradual fall in pressure due to the movement of lows. As air converges at an angle to the isobars of a low-pressure system, the pressure is reduced, and the air expands and cools very slightly adiabatically. In the case of the isallobaric effect the air is allowed to expand as the pressure falls due to the horizontal movement of the low, and the air cools adiabatically. The isobaric effect is negligible, and the isallobaric effect produces fogs in only rather rare occasions when the relative humidity is very high and the isallobaric gradient is steep without the winds also being too strong. However, the possibility of these effects should be considered since they may combine with other fog-producing

tendencies so as to bring about fog as the product of a composite action when none of the separate agencies are individually strong enough to result in fog formation.

C. Fogs due to Nonadiabatic Processes. Cooling from an underlying surface is one of the primary causes of fog. Such cooling may result when warm, moist air is displaced horizontally (advection) so that it comes in contact with a cold surface, or when the surface already underlying the air cools by radiational processes.

1. Advection-fog Types. Advection-fog types are caused by the transport of warm, moist air over cold surfaces. They are classified as follows:

a. Monsoon Fog. In some parts of the world there is an upwelling of cold ocean currents along the coasts. As the land heats during the day a pressure gradient is formed from the sea to the land. Relatively warm, moist air is drawn over the cold coastal ocean current by the onshore gradient, and fog may result. Fog formed in this manner will usually be rapidly dissipated as it comes ashore over the warm land. Monsoon fog may never be expected in very low latitudes or in high latitudes. In the former, the temperature gradient between the coast and the sea is too slight and, in the latter, the specific humidity of the air is too low.

b. Land- and Sea-breeze Fog. During the summer months warm, moist air may be carried out over the relatively cool sea surface. Condensation may occur over the cool sea surface and the resulting fog may be brought inland during the afternoon by the returning sea breeze. When the winds are moderate, or strong, only stratus clouds may form because of the turbulence maintaining a strong lapse rate in the lower levels over the sea. (When the winds are light a dense fog may form as the air travels seaward.) In cases when the pressure gradient is weak a gentle onshore wind may persist for several days causing a prolonged fog. Land- and sea-breeze fogs are coastal phenomena. They may also occur where there are large inland bodies of water such as along the shores of the Great Lakes where they are called shore- and lake-breeze fogs. (Fig. 104)

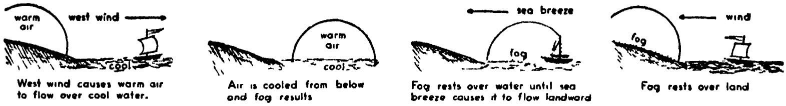


Fig. 104. Land- and sea-breeze fog.

c. Sea Fog. When warm, moist air passes over cold ocean currents, condensation results and sea fogs are formed. Sea fog is often carried inland. Such fog will be more persistent in higher winds if the temperature difference between the wind and the ocean current over which it is passing is great. Turbulence will dissipate the fog near the surface and cause the formation of a layer of stratus clouds by carrying warm air downward from aloft. Sea fog is not merely a coastal-type fog. It may be formed anywhere over the sea if ocean currents with contrasting temperatures are adjacent to each other. Sea fogs are very prevalent off the northern California coast and over the Grand Banks.

d. Tropical-air Fog. As tropical air moves from lower to higher latitudes the gradual cooling, due to latitudinal displacement, may result in fog formation. This is one of the most common fogs found over the open sea. Over the land, turbulence may produce enough mixing to prevent such condensation near the ground. The low stratus clouds that result are hazardous to aviation as they may form practically instantaneously over a large area within the air mass. Tropical-air-type fogs may also be formed in returning polar air as it enters the circulation of the Azores High and is brought northward from southern latitudes. This fog type will form more readily in winter than in summer. Tropical-air fog may be maintained in strong winds due to the air's inherent stability in the lower levels, as well as its increasing stability as it moves to progressively colder regions.

2. Radiation Types. Fogs of this type are caused by the cooling of surfaces by radiation. The layer of air in contact with such surfaces has its temperature lowered by conduction and condensation often results.

a. Ground Fog. When the wind velocity decreases in the evening, as it normally does, conditions become favorable for the formation of ground fog. As the ground cools by radiation, the lower layers of air are cooled by conduction. Lack of strong turbulence, initial, high relative humidity, clear skies, and constant or increasing humidity along the vertical in the lower layers represent favorable conditions for the formation of ground fog. Cloudless skies and lack of turbulence are most characteristic of anticyclones during the colder seasons.

When maritime air stagnates over continental areas in fall, winter or early spring, radiation ground fog will form. Clouded skies reduce the probability of ground fog because of their counterradiation effect. Radiation ground fog forms first in low places due to katabatic wind drainage. Subsidence in the upper layers of the atmosphere dissipates the clouds and permits free radiation of surface heat into space, thus increasing radiation-fog possibilities.

b. High-inversion Fog. This is a type of radiation fog. As the result of long-continued net loss of heat by radiation over continental areas during the winter, dense fogs may be formed. During the day, the surface may be heated enough to dissipate the fog leaving low stratus clouds. At night, with further radiational cooling of the ground, fog reforms. When subsidence, as in a stagnated anticyclone, occurs over an area where the above conditions are favorable, a fog of several days' duration may result. In a region of anticyclonic activity, inversions, which are first formed by surface cooling, are intensified by subsidence and radiation from the upper surface. Below the upper air inversion the lapse rates may become rather steep. As a result, dust particles and hygroscopic nuclei may be carried aloft to the base of the inversion where they serve as nuclei for condensation. Due to the fact that the specific humidity is fairly constant through the lower layers, while the temperature decreases aloft, the relative humidity increases up to the base of the upper-air inversion. Hence, high inversion fog will usually first be formed at the base of the inversion. (Fig. 105)

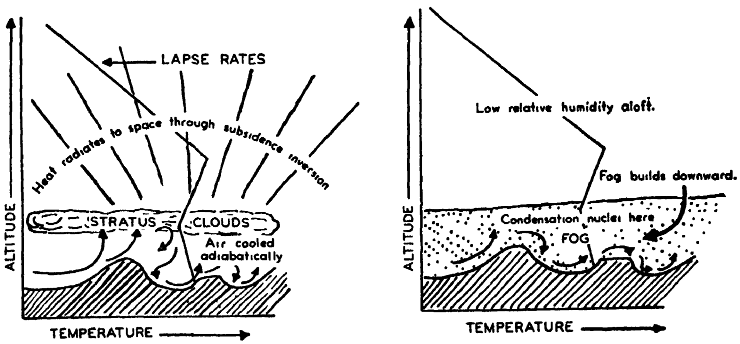


Fig. 105. High-inversion fog.

c. Ice-crystal Fogs. Over cold continents the temperature may drop low enough so that the water vapor of the air sublimates on sublimation nuclei. Since only a small amount of water vapor is required to produce ice crystals in sufficient size and number to reduce the visibility below the fog limit, ice-crystal fogs often form when the temperature falls to — 20° C. and lower. Ice-crystal fog, in contrast to water fogs, are not dissipated over snow-covered ground. Fog of this type may be observed at temperatures as high as — 10° C. but the greatest frequency occurs at lower temperatures.

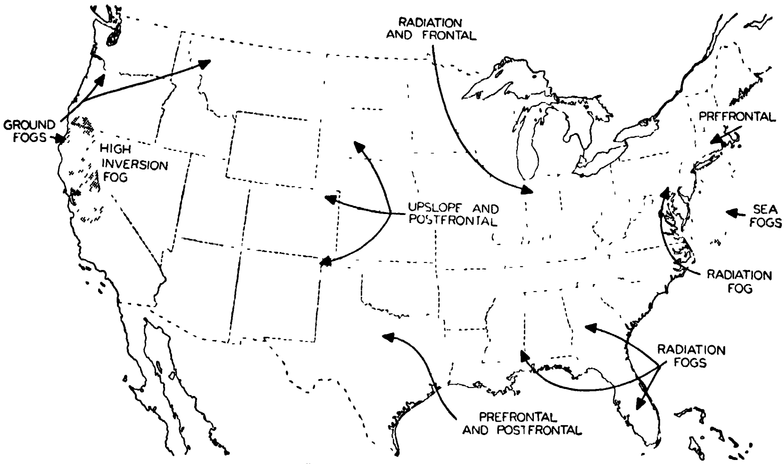
III. FOG-DISSIPATING PROCESSES

Fog formation is dependent upon whether or not the fog-producing processes outweigh the fog-dissipating processes. Thus, if any accuracy is to be maintained in fog forecasting, the fog-dissipating processes must be given full consideration.

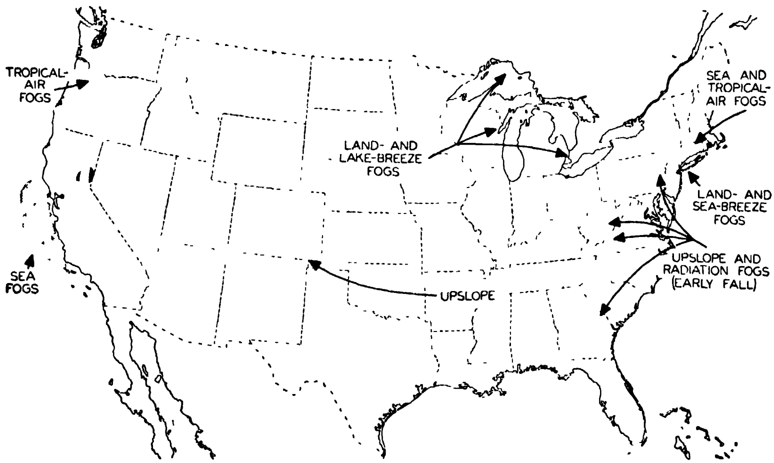
A. Sublimation or Condensation on Snow-covered Surfaces. Fog can only persist over the snow when the air is steadily cooled and there is a sufficient downward flux of moisture from overlying layers to compensate for the loss of moisture caused by condensation on the snow. This condensation effect takes place because of the snow's low vapor pressure. Since the air loses its moisture to the snow surface, its relative humidity is constantly reduced and condensation in the air is minimized; therefore, fog formation is prevented. As the temperature of snow-covered surfaces decreases, the vapor pressure of the snow decreases and the fog-dissipating effect becomes stronger until the temperature is finally reached for the formation of ice-crystal fogs. Such fogs, since they are formed by sublimation processes, are not dissipated by the snow effect. As the temperature falls below 0° C. the tendency for condensation of water-vapor fogs on the snow increases, while above 0° C. the melting snow has a dissipating effect on fog; hence, the highest frequency of fog over snow-covered ground occurs in spring when the air temperature is close to 0° C. As the diurnal temperature range of cold air is very low a fog will not form over a snow-covered surface due to nocturnal cooling alone.

B. Fog-dissipation due to Absorption of Radiation. One of the major causes of the dissolution of fog is the absorption of radiation by the fog itself, or by the underlying surface which then reradiates the energy and dispels the fog. Thus, radiation ground fog is soon dissolved when the sun rises and begins to heat the air at the surface.

C. Fog-dissipation by Advection and Vertical Mixing. The advec-



A. FALL AND WINTER FOGS



B. SPRING AND SUMMER FOGS

Fig. 106a and b. Some characteristic fogs in the United States and the seasons of their greatest prevalence.

tion of cold air containing fog over warmer surfaces often results in the fog's dissolution. In addition, as indicated in the previous discussion, vertical mixing is one of the most important fog-dissipating processes. This is accomplished by the modification, or destruction, of the ground inversion by the flux of warmer air from aloft and, also, by the thinning of the fog due to its distribution through a deeper layer of air.

D. Minor Fog-dissipating Processes. Fog may be dissipated, to some extent, by adiabatic heating due to downslope motion, flux of air across the isobars to higher pressure, and rising pressure.

IV. FOGS IN THE UNITED STATES (Fig. 106 A and B)

Locale	*Predominating Fog*	*Secondary Fogs*
New England	Land- and sea-breeze	Continental radiation warm-front fogs
North Pacific Coast	Tropical-air fogs	Sea fogs
Appalachian Valleys	Radiation fogs	Prefrontal warm-front
Pacific Coast Valleys	High-inversion fogs	Shallow ground fogs
California Coast	Sea fogs	Radiation fogs
Middle Atlantic Coast	Sea fogs	Radiation and pre-frontal types
Great Lakes Region	Land- and lake-breeze fogs	Steam fogs over lakes Radiation fogs on land
South Atlantic and Gulf Coasts	Sea fogs	Radiation fogs
Atlantic Coastal Plain	Ground fogs	Upslope fogs
Great Plains	Upslope fogs	Radiation fogs
Middle Valley	Radiation fogs	Frontal types

V. FORMATION OF ICE ON AIRCRAFT

One of the major hazards of winter flying has been the imminent possibility of encountering icing conditions and being forced to land under adverse circumstances. Like fogs, icing conditions are largely dependent upon the influence of turbulence in determining their severity. However, unlike fogs which are dissipated by severe turbulence, the amount of icing is increased within turbulence clouds. Cold air does not have a high moisture content. Hence, if condensation takes place only at the freezing level, the amount of moisture available for ice formation will be limited. If, on the other hand,

condensation occurs at a lower and warmer level more moisture will be available than in the cold air aloft. When this condensed moisture is carried aloft by severe turbulence to near the freezing level it is then available for heavy ice formation by the processes which are to be described.

A. Types of Ice. There are two predominant types of ice particularly dangerous to aviation. Clear ice is formed when large, supercooled, liquid drops are ruptured by impact with the aircraft and flow back over the surface where freezing produces a uniform layer of transparent ice. This type is very tenacious and, since it is nonporous, it is also very heavy. It does not interfere with the aerodynamic characteristics of airfoils as much as rime ice, the other type, but it is more difficult to dislodge and rapidly adds prohibitive weights. Rime ice is formed when tiny droplets freeze without complete rupture. The texture is granular and pure rime ice is a white, opaque solid. Ice of this type builds up along the leading edges of the airfoils and tends to destroy their aerodynamic effectiveness. Due to its granular structure it is more easily removed than clear ice.

1. Glaze (Clear Ice). This is a transparent, or translucent, coating of ice which characteristically forms within dense clouds consisting of large, supercooled drops. Inasmuch as the drops from which glaze ice is formed are large, this type of icing is found in convective clouds where the turbulent currents are severe. Glaze ice may also be encountered over the summit of hills where clouds are being maintained by orographic lifting.
2. Rime. Opaque, white ice with a granular texture is called rime ice. Its rough surface increases the drag on airfoils. Airplanes with heavy wing-loading values are endangered by the formation of ice of this type. Rime ice may be formed within filmy clouds consisting of small supercooled drops. Thus, stratus-type clouds will yield rime ice when the temperature within them falls within the icing range, since only mild vertical currents are found in stratus clouds and the large droplets, necessary to form clear ice, could not be supported.
3. Heavy, Clear Ice. This ice forms when an aircraft is flying through a layer of the atmosphere the temperature of which is below the freezing point, and through which rain is falling. Obviously, the greatest danger from ice of this type is sudden added weight. When ice is picked up under these conditions immediate action should be taken to rectify the circumstance as the plane will very quickly become completely iced and unflyable. Heavy, clear ice may consist of a mixture

of glaze and rime ice in which case the aerodynamic characteristics of the airfoils are also impaired by the accumulation. Icing of this type is usually encountered in the cold air in advance of a warm front in the late fall or early spring.

4. Frost. There is little danger from frost formation while in flight. However, since its presence may impede the take-off, all frost should be removed prior to the take-off. Frost is formed by direct sublimation upon the surface of the aircraft. Thus, when an airplane has been flying in very cold air and then enters a warmer, more moist stratum, frost may form on its surface. Frost formed in this manner, however, is of little consequence as it either rapidly blows or melts away.

B. Conditions Conducive to Ice Formation.

1. Temperature. When the temperature is between 34° F. and 26° F. icing conditions are at their maximum, although severe icing is possible throughout the entire range from 35° F. to 10° F. when other conditions are favorable. There is always the possibility also of the presence of supercooled water droplets that will freeze on contact at much lower temperatures. At temperatures between + 5° F. and — 4° F. clouds tend to be formed of ice crystals. On the other hand, water clouds have been found to exist with supercooled water droplets at temperatures as low as — 55° F. When water exists at a temperature lower than 32° F. it is in a very unstable state. Any kind of disturbance will tend to cause ice formation. Since 80 calories per gram must be removed to produce freezing, some means must be furnished to absorb this heat if freezing is to occur. This change of state (water to ice) may be caused by:

   a. Evaporation of Some of the Drops Due to Impact. At 0° C. there are 595 calories required to vaporize one gram of water, while only 80 calories are liberated when one gram of water changes to ice. Thus, the vaporization of one gram of water will absorb enough energy to cause the formation of over seven grams of ice. The evaporation of about 12 per cent of an ice-and-water mixture would be sufficient to freeze the remaining 88 per cent.

   b. Impact with cold surfaces of the plane, which have been cooled by aerodynamic reactions or passage through the cold air, is an effective method by which the heat liberated from ice formation is absorbed.

When other conditions are favorable, ice will continue to form as long as this latent heat can be dissipated.

2. Supercooled Droplets in Convective Clouds. The turbulence in convective clouds may carry large drops of water upward to freezing zones while they are being supercooled. Conditions favorable to this phenomenon are characteristic of cold fronts, orographic and cumulonimbus clouds.
3. Freezing Rain. Usually in advance of a warm front, rain falling through cold air often freezes upon contacting a moving plane. Icing of this type is extremely rapid.
4. Moist Snow Flakes. Partially melted snow may be quickly changed to ice by contact with rapidly moving cold surfaces.
5. Visible Moisture below Freezing. Icing conditions are likely whenever there is visible moisture at below-freezing temperatures. As previously explained, conditions are most favorable for icing between 35° F. to 10° F.

C. Conditions When Ice Formation Is Unlikely.

1. Very Low Temperatures. When flying through an air mass which is far below freezing, ice formation is unlikely.
2. No Visible Water Vapor. If visible water vapor is not present the air is usually too dry for serious icing dangers.
3. Air Masses Containing Frozen Particles. There is but little risk of ice formation on aircraft in air masses where the particles are already frozen. Such conditions are characteristic of cirrus-type clouds.

D. Forecasting Ice Formation. In order to make accurate forecasts of ice formation, detailed upper-air information should be available. However, forecasts of possible icing conditions can be made on the basis of certain other observations. Icing conditions require the suspension of large quantities of liquid water in the clouds. Since ascending air is necessary to accomplish this suspension, icing conditions are to be expected when ascending air currents are to be found. Warm fronts and clouds formed by orographic lifting are the most formidable producers of icing conditions.

E. Summary of Dangers of Aircraft Icing.

1. Aerodynamic Effects. Accumulation of ice on airfoils may impair their aerodynamic effectiveness. In addition, the drag of an airplane becomes greater after ice is formed. Increased drag tends to reduce speed, until eventually a maximum of icing is reached, beyond which further flight becomes impossible.
2. Increased Weight. Obviously, increased weight is dan-

gerous to all types of aircraft. This is especially true of aircraft already loaded to capacity.

3. Propeller Icing. Ice formation on propellers decreases their effective thrust. In addition, the ice accumulation is often not symmetrical. When more ice forms on one blade than on the other the engine may become unbalanced and dangerous vibration result.
4. Carburetor Icing. Because of the cooling inherent to passage through the carburetor venturi, and also because of heat extraction from the carburetor caused by vaporization of the fuel, carburetors are easily subject to icing. What actually happens in an engine carburetor is that, under the influence of these effects, air from the engine air-induction system is cooled below its dew-point temperature and the precipitated moisture freezes. Since the temperature of air entering a carburetor may drop as much as 10° C. to 30° C. the air need not have a high, initial relative humidity, although a high relative humidity is conducive to carburetor icing. Carburetor icing is combated by the use of carburetor heaters.
5. Mechanical Effects. Moving parts of aircraft such as rudders, elevators, and ailerons may become restricted in movement by ice accretion. Other parts that are interfered with mechanically by ice accretion include the pitot-static tubes used in connection with various flight instruments such as the airspeed indicator. Radio antennae, and pilot's and bombardier's windshields are also restricted in function by icing. The icing of external fittings of flight instruments represents a very serious threat to air safety if allowed to continue since faulty readings may cause serious flight miscalculations. The icing of moving parts is usually not of great importance since the aircraft will, in most cases, be forced to the ground by ice accumulation prior to the time that the effect becomes noticeable.

F. Methods for Avoiding Icing. An observance of the following rules should enable a pilot to avoid icing conditions, or to extricate himself when he finds that icing is taking place.

1. The thermometer should be watched at all times when flying through cloud layers. If the critical temperatures for icing are encountered it should be remembered that the icing zone may extend through a maximum layer of about 8000 ft.
2. If the ice is encountered while flying through convective, broken clouds the pilot should fly out of them and continue to avoid them.

3. Fly over orographic, hill clouds rather than through them. If they extend to a high level an attempt should be made to fly through them only at the higher levels unless the lower altitudes are above freezing.
4. Remember that an aerodynamically clean plane can fly for at least ten minutes through the icing conditions characteristic of stratus-type clouds. Since stratus clouds with icing usually occur at low levels this time interval should be sufficient to enable the plane to clear the icing zone.
5. Keep alert for ice formation when flying over hills, in rain, sleet or heavy, dense clouds if the temperature is within the critical icing range.
6. If ice is encountered in flying through unbroken, or partially broken cloud systems, the correct procedure is to descend if it is known that there is sufficient clearance for flying beneath the clouds, and that there is no freezing rain. When over the ocean, or near the ocean, icing may often be avoided by flying close to the ocean surface.

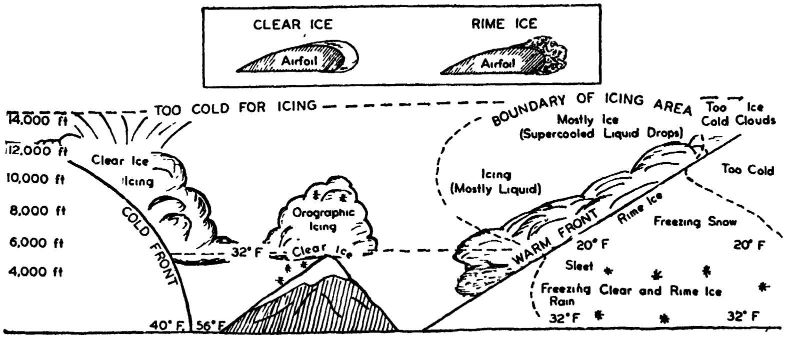


Fig. 107. Icing conditions.

7. When ice is encountered under the above conditions, but it is known that there is not sufficient clearance under the cloud, the procedure followed will depend on the type of craft being flown. If the airplane has little reserve power an attempt should be made to gain altitude as rapidly as possible. This may be successful in bringing the craft out of the icing zone. If ice continues to accumulate, a course must be set for the nearest available landing field before the plane becomes unmanageable. When flying a plane with adequate reserve power, the icing zone will undoubtedly be flown out of by the above procedure. It should be remembered, however, that if the plane is rising along the discontinuity sur-

face of a warm front, it will be very difficult to transverse the icing zone quickly enough to avoid dangerous icing. In climbing, then, the thermometer should be constantly watched, and if the temperature does not seem to be falling rapidly enough, reverse the plane's direction and continue to climb.

8. In all circumstances, if icing starts, the de-icing equipment must be put into operation immediately and some positive action must be taken to extricate the aircraft from the icing zone. Indecision and delay often prove fatal. (Fig. 107)

TEST QUESTIONS ON FOGS AND ICING CONDITIONS

1. Fogs are classified according to (size of particles, air temperature, fog-producing processes, moisture of the air, fog-dissipating processes)
1. ________

2. Evaporation fogs are formed by vaporization into (warmer air than the liquid water, colder air than the liquid water, air of the same temperature as the liquid water). 2. ________

3. Vapor pressure (increases, remains the same, decreases) with a rise in temperature. 3. ________

4. Prefrontal fog is most often formed when the air in the cold sector is (stable, neutrally stable, unstable). 4. ________

5. In the case of frontal fogs the precipitated moisture is (warmer than, the same temperature as, colder than) the air through which it is falling. 5. ________

6. (Strong, medium, weak) turbulence is conducive to the formation of frontal fogs. 6. ________

7. Steam fogs usually occur when there are (strong, medium, negative) lapse rates. 7. ________

8. Steam fogs will occur when the vapor pressure of the overlying air is (higher than, the same as, lower than) that of the water over which it is lying. 8. ________

9. Steam fogs are (always, sometimes, never) found in arctic regions.
9. ________

10. (Extreme, slight, medium) differences between the air and the water surface are conducive to the formation of steam fogs.
10. ________

11. Rain-area fog is caused by (evaporation, adiabatic processes, non-adiabatic processes). 11. ________

12. Adiabatic fogs will occur when the air has a (high, low, medium) initial relative humidity. 12. ________

13. Isobaric and isallobaric fogs are both caused by (evaporation, adiabatic processes, nonadiabatic processes). 13. ________

14. Upslope fogs are usually (shallow, medium, deep) fogs. 14. ________

15. Upslope fog may have its formation accelerated by (high temperatures, low humidity, strong winds, rough terrain, moderate winds). 15. ________

16. Convergence at fronts will in most cases produce (fog, low stratus, high stratus, clearing conditions). 16. ________

17. Advection refers to (horizontal, vertical, angular) movement of air. 17. ________

18. Isobaric and isallobaric processes (often, seldom) produce fogs as solitary effects. 18. ________

19. Cooling from an underlying surface is a(n) (adiabatic, nonadiabatic, vaporization) process. 19. ________

20. One of the following fogs (prefrontal occlusion, convergent, monsoon, upslope, isallobaric) is produced by nonadiabatic processes. 20. ________

21. Monsoon fog characteristically occurs in (high, middle, low) latitudes. 21. ________

22. Land- and sea-breeze fogs form when the winds are (high, moderate, light). 22. ________

23. Sea fog is a(n) (radiation, advection, vaporization) type fog. 23. ________

24. Tropical-air fog is more often found over the (land, sea). 24. ________

25. The air in which tropical-air fog is found becomes (more, remains the same, less) stable as it moves to higher latitudes. 25. ________

26. Radiation-type fog is a(n) (evaporation, adiabatic, nonadiabatic) type. 26. ________

27. Radiation fog is formed most often on (overcast days, clear days, overcast nights, clear nights). 27. ________

28. Ground fog is formed when the humidity (increases, decreases) along the vertical. 28. ________

29. Radiation fog occurs most characteristically in (continental, dry, polar, maritime) air masses. 29. ________

30. In the case of high-inversion fog the inversion usually (extends to the ground, is a subsidence inversion aloft). 30. ________

31. High-inversion fog forms first at (the ground, the base of the inversion, intermediate levels). 31. ________

32. Ice-crystal fog forms when the air has a (high, low, medium) specific humidity. 32. ________

33. Fog formation is (accelerated, retarded) over snow-covered ground at temperatures below freezing. 33. ________

34. Name four main fog-dissipating processes. 34. ________

35. Icing conditions are (increased, decreased, remain the same) with turbulence. 35. ________

36. Name the two main icing types. 36. ________

37. List the temperature range most conducive to icing. 37. ________

38. The most adhesive ice type is (glaze, rime, heavy clear ice, frost). 38. ________

39. List four conditions conducive to icing. 39. ________

40. List three conditions when icing is unlikely. 40. ________

CHAPTER X

WEATHER MAP ANALYSIS AND FORECASTING

I. ANALYSIS OF THE WEATHER MAP

The synoptic chart has entered upon its surface, in coded form, a large number of observations taken simultaneously at many stations all over the continent and from ships in the adjacent oceans. The meteorologist's task is to interpret the information encoded on the map by some consistent method of analysis and then to issue a forecast based upon this analysis, comparison of past trends, and scientific interpretation of future possibilities. The analysis includes an evaluation of the encoded data so that observational and personal errors may be anticipated and corrected as their incongruities become apparent. The analysis should be consistent with the actual reported weather conditions, as well as with the principles of air-mass and frontal analysis. Careful study should be given to all data available, such as upper-air wind charts, pseudo-adiabatic diagrams, isentropic charts and previous synoptic charts, preceding and during the actual analysis of the current synoptic chart. Fronts should only be drawn on the chart when there is definite evidence of their presence, and when they are consistent with the principles of air-mass analysis. Fronts drawn on the chart merely on the basis of wind shifts, or some other solitary determining factor, are not only valueless but are often extremely misleading.

II. DRAWING ISOBARS

The isobars, since they are lines drawn between points of equal pressure, give a definite pattern of the pressure system and indicate paths of major air flow. Because of their importance to the analysis they should be drawn with special care. Isobars are, in most cases, drawn for every 3-mb change in pressure for pressures divisible by three. For example, 999 mb which is encoded on the synoptic chart as 990 (the first figure or first two figures for pressures above 1000 are dropped and a place is added for tenths of a millibar) might be the first isobar drawn for a low-pressure area. The next isobar would be for 1002 (encoded as 020). Isobars are drawn with a lead pencil of medium hardness. It is a good practice to draw them lightly in the vicinity of fronts where there is some uncertainty. In other than

frontal positions the isobars may be drawn in full. When drawing isobars the analyst should start where the analysis is the simplest. In the United States, the most desirable place to start the analysis is usually the central part of the country. The first isobars on the map should never be drawn in the Rocky Mountain region, due to the fact that barometric reports are in many cases erratic in that area.

A. Preliminary Methods. After sketching in the probable fronts as previously described in Chapter VII, the chart is surveyed and high- and low-pressure centers are noted. The first isobar for both highest and lowest pressures is then drawn. If there is any doubt as to the nature of the pressure field it is good practice to cover the chart with an isobaric skeleton before sketching in the permanent isobars.

B. Placing of Isobars. Be sure that pressures on one side of an isobar are always above, and on the other side that they are always below that of the isobar. For example, the isobar for 1020 mb may pass between two stations one of which is 1019 mb and the other 1020.7 mb. It is not necessary to take proportional parts to establish the path of an isobar between stations except when the stations are far apart and it becomes necessary to pass several isobars between them. See the example given below. (Fig. 108)

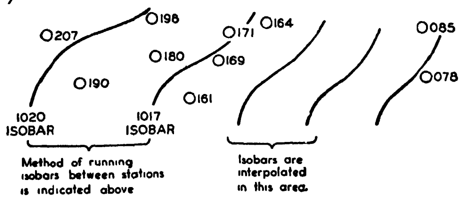


Fig. 108. Placing of isobars.

C. Intervals between Isobars. The pressures on consecutive isobars always differ by the same standard interval (3 mb) except at a col where they have the same value in the direction across the col. For example, two 1011 isobars may be drawn side by side as in the illustration. (Fig. 109) In this case each of the 1011 isobars partakes of the circulation of different systems.

D. Isobars and Wind. In accordance with Buys-Ballot's law, isobars should be drawn to fit the winds as nearly as possible. There should be an allowance made for a slight flow across the isobars from high pressure to low. This flow amounts to about 35 degrees over the land and 20 degrees over the ocean. Except where they occur over mountains, steep pressure gradients will have smooth isobars. The stronger the flow of air, the smoother

the isobars should be drawn. When the pressure gradient is at a minimum as over "flat" summer maps, irregular isobars may actually occur. To test the validity of such irregularities intermediate isobars may be drawn to see if the original irregularity is substantiated. In the summer, such variances may indicate a possible thunderstorm area.

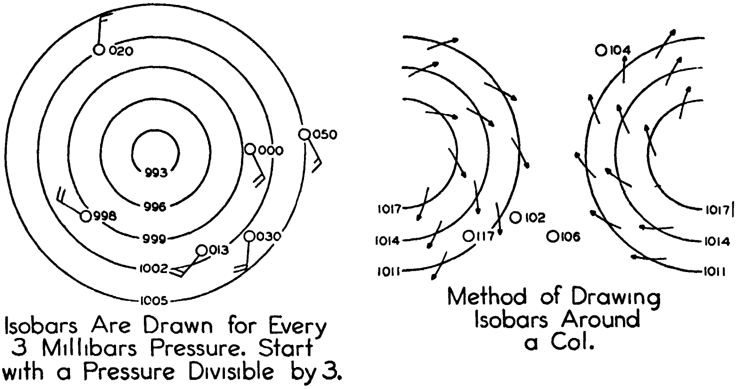


Fig. 109. Intervals between isobars.

E. Nature of Isobars. Isobars must always be either simple, curved lines with loose ends at edges of chart, or simple, closed curves. Isobars are left open at the sides, top and bottom of charts because of insufficient data to warrant their closing. (Fig. 110)

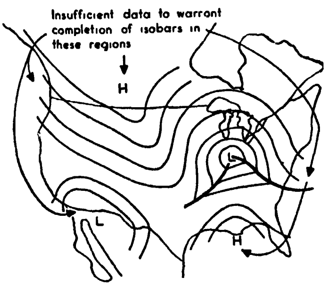


Fig. 110. Synoptic chart showing open isobars at sides and top of map, and closed systems in interior.

F. Closing of Isobars. Isobars must never touch or cross, except when two ends of the same isobar join to make a closed curve. (Fig. 111)

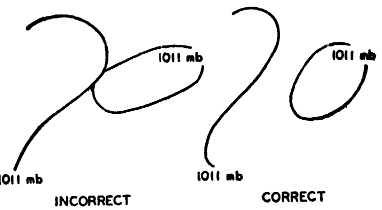


Fig. 111. Closing of isobars.

G. Smoothing of Isobars; Eliminating Errors. Simple isobars are much more probable than complicated isobars. Certain errors, inherent to pressure reports, often make the path of isobars unnecessarily complicated. In such cases, an understanding of the sources of probable error will aid in smoothing out the isobars. (Fig. 112)

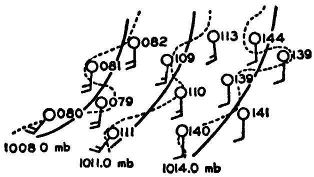


Fig. 112. Method of smoothing isobars.

Dotted lines are isobars before smoothing. Solid lines represent the isobars after meaningless irregularities have been eliminated by smoothing.

1. Personal Errors. If you suspect personal errors it is good practice to compare the present station reading with a previous station reading. Errors will become recognizable as not being consistent with the barometric tendency. If such personal errors are confirmed in this manner the pressure report for that station may be crossed out and disregarded. Irregularities that show no systematic arrangement should be smoothed out.
2. Errors of Reduction to Sea Level. These errors may be detected at stations of considerable altitude. Errors of this type increase with the departure of the air temperature from the mean temperature used for reduction purposes. Stations over 1500-ft. altitude can seldom be relied upon for pressure reports.
3. Errors of Ship Reports. Many apparent errors in ship reports are due to errors in reporting the position of the ship. Often if the report is moved 5° or 10° either in latitude or longitude it will be in agreement with the pressure system.

H. Isobars at Fronts. Isobars in the vicinity of fronts should be drawn so as to bring out the frontal discontinuity in the horizontal pressure gradient. Hence, correct isobars should always be V-shaped at a front with the point of the V pointing toward the high pressure. A shearing motion is one of the fundamental properties of fronts. If there were no kinks in the isobars at fronts, there would be no shearing motion. Isobars in warm sectors are usually almost straight lines. Isobars in the cold air are curved, with curvature decreasing toward the warm front. As fronts must always be situated in the pressure trough, they must be situated nearest the station which has the lowest pressure. (Fig. 113)

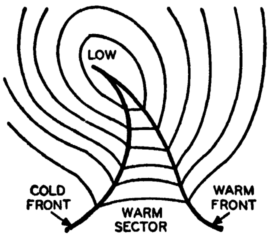


Fig. 113. Isobars at fronts.

I. Isobars—Insufficient Reports. Isobars should be drawn first in those areas where the analysis is simplest. At sea, the isobars should first be drawn where the observations are most numerous and the winds are the strongest. (Fig. 114)

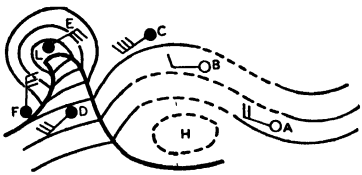


Fig. 114. Drawing isobars in regions of insufficient reports.

In Fig. 114 the pressure field should be first constructed around stations C, D, E and F and, finally, around A and B.

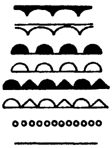
J. Sketching Isobars. Isobars should be drawn in with a firm, smooth freehand stroke. When isobars are drawn in this manner, providing they are technically correct, a good useful picture of the pressure system is obtained.

III. METHODS OF INDICATING VARIOUS PHENOMENA ON THE WEATHER MAP

A. Fronts and Precipitation Areas.

1. Fronts.

TYPES OF FRONTS	ON HAND-DRAWN CHARTS	ON PRINTED CHARTS
Cold Front at the Ground	Continuous Blue Line	
Upper-air Cold Front	Broken Blue Line	
Warm Front at the Ground	Continuous Red Line	
Upper-air Warm Front	Broken Red Line	
Occluded Front	Continuous Purple Line	
Upper air Occluded Front	Broken Purple Line	
Indistinct Front	Dotted Line	oooooooooooo
Stationary Front	Alternate Red & Blue Lines	



2. Precipitation Areas.

Area of continuous precipitation	Solid green shading.
" " intermittent "	Green hatching.
" " fog	Light red shading.
" " showers	Green shower symbols over area.
" " thunderstorms	Green thunderstorm symbols over area.
" " drifting snow	Green drifting snow symbols over area.
" " drizzle	Green drizzle symbols over area.
" " dust	Green dust symbols over area.

B. Designation of Air Masses. The various symbols for air-mass designation have been given in a previous table. On working charts, these air masses have, in addition, the following color designations. Air from arctic or polar sources is marked in blue. Air from tropical or equatorial sources is marked in red.

IV. SUMMARY OF STEPS INVOLVED IN PREPARING THE SYNOPTIC WEATHER CHART

A. All station entries are first made on the map.

B. At least two of the previous maps are posted for comparison of historical sequence.

C. After surveying pressure systems of the preceding maps, the pressure centers of the current map should be located. The first isobar for each system so located is then drawn lightly on the map.

D. Precipitation and fog areas should be shaded as they serve to give clews as to the location of fronts.

E. On the basis of probable movement from previous positions

and the general characteristics, the fronts should be sketched in lightly. In locating and placing the fronts, and in forecasting their probable movement and resulting weather, all types of data available should be employed.

F. The pressure systems should then be completed by drawing all remaining isobars.

G. The pressure at the centers of highs and lows is marked at those points. The symbols should indicate the approximate axis of the pressure system. Highs are identified with a blue H and lows with a red L. Arrows in black ink are used to predict the movement and future positions of pressure centers and fronts. (Fig. 115)

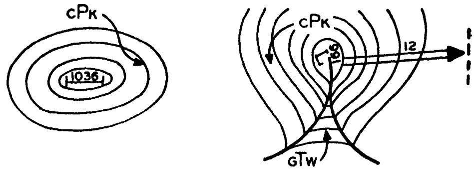


Fig. 115. Method of marking the centers of highs and lows and indicating probable movement for a twelve-hour period.

H. Air masses are marked with appropriate symbols and colors. Arrows are employed to indicate the path of flow of the air masses.

V. FORECASTING

The commercial product of the science of meteorology is forecasting. At the present time forecasting is not truly a scientific procedure. Too many unpredictable variables must enter into every forecasting event to enable the forecaster to make any true claim for scientific accuracy. Nevertheless, the scientific method is now being used with gratifying results in prognosticating the illimitable vagaries of the weather. Considerable progress has been made since the time of the quaint, little "sure forecast." A little statue of a donkey with a rope tail was exposed to the weather. The following legend was inscribed on a placard under it.

If tail is dry	Fair
If tail is wet	Rain
If tail is swinging	Windy
If tail is wet and swinging	Stormy
If tail is frozen	Cold
If tail is missing	Hurricane

A. General Forecasting Method.

1. Construct a weather chart and analyze its various features. In the analysis and forecast all the data, science and experience available to the forecaster should be utilized.
2. Project this analysis into the future so as to prognosticate future changes in the present weather. Maintain an alertness to all indications both local and synoptic so as to keep your finger on the pulse of weather developments. A good forecaster does not try to make his forecast with the shades drawn.
3. Make a complete analysis of irregularities and variances from your actual forecast. Make a sincere attempt to trace the source of your error so as to avoid a repetition of the error under similar circumstances. This is known as "aftercasting." Constant aftercasting enables the forecaster to gain experience and avoid repeating errors.
4. Check teletype sequence reports for the development, path and movement of pressure areas and storm centers. Teletype sequences are more recent than the map and they will help keep the weather-map analysis up to the minute. Special phenomena such as thunderstorms may be followed by sequence reports.
5. Check surface observations with upper-air data. No aid should ever be overlooked. The system of analysis being used is air-mass and frontal analysis, so it must be remembered that there cannot be a legitimate front unless there is a change in the air mass. Hence, all data available should first be utilized to identify the air masses.
6. The type of weather to be expected in connection with frontal areas is dependent upon the nature of the interacting air masses. All warm fronts will not be characterized by continuous light to moderate rain nor all cold fronts by showers.
7. Special attention should be given to the topography of the section for which the forecast is being made. Mountain barriers often act as boundaries for cold air masses and serve to desiccate other air masses as they pass over them. In addition, the lee sides of high mountain ranges often serve as areas of frontogenesis.
8. The general circulation is important in determining the prevailing weather type over many areas. For example, along the Pacific Coast of the United States, Tropical Maritime air cannot move ashore when the Pacific anticyclone is located offshore.

9. The forecaster should examine all frontal areas on every map since fronts may change character from one map to the next. A portion of a cold front may develop warm-front characteristics when waves form along the front.
10. At all times a close study should be made to determine signs of frontogenesis, frontolysis and other dynamic phenomena apt to have a variant effect on the natural progression of weather events.

B. General Types of Forecast.

1. General Inference. A general description of the pressure distribution and position of fronts is made. This is followed by the probable movements and developments for a period of 24 hours or more.

   Example of General Inference: Polar Continental air extends over the North Atlantic states and as far west as Detroit. Polar Pacific air covers the South Central states and Tropical Gulf air is over the Mississippi Valley region. An occluded front passed over the station during the night, while a warm front is now moving at a moderate speed up over South Carolina and should pass over this station early tomorrow morning. A cold front now extends southward from Chicago to northern Texas; it is expected to move northeastward and probably extend from central Maine south-southwestward along the Atlantic Coast by noon tomorrow.

2. Area Forecasts. In this type of forecast the general indications of flying conditions to be expected over substantial area, with little attention to detail, are considered.
3. Local Forecasts. Local forecasts are detailed prognostications of the anticipated conditions in the immediate vicinity of a flying center for periods of 12, 24 or 36 hours.

   An Example of a Local Forecast:

Today until 1800

Flying Conditions	*State of Weather*	*Surface Winds*	*Temp.*
Good	Partly cloudy	N.W. 5 to 10 m.p.h.	Max. 60° F.

Detailed Forecast: Partly cloudy sky with decreasing low and intermediate cloudiness. Northerly surface winds averaging 8 m.p.h. with gusts to 12 m.p.h. Fair visibility and good flying weather. Little change in temperature.

The above would normally be followed by detailed forecasts for the following two 12-hour periods.

4. Route Forecasts. Route forecasts are for anticipated conditions along a specific route for the duration of a particular flight. Cross-section maps are usually issued for route forecasts.

C. The Rules of General Inference. Many different types of rules have been written to facilitate forecasting procedure. Rules of an empirical nature are always developed by the forecaster for use in the vicinity of his forecast area. In many cases these local empirical rules have been enlarged upon in an attempt to anticipate major weather changes. Empirical rules are often of doubtful value since, while they may be true for one set of circumstances, they may be incorrect for another slightly different combination. Inasmuch as the scientific background for such empirical rules is not fully understood they are not adaptable. On the other hand, Petterssen and other dynamic meteorologists, such as Brunt and Sir Napier Shaw, have mathematically derived various formulas which may be applied to the field of pressure. Because these formulas are actually based on the kinematical and dynamical properties of the field of pressure, rules derived from them are objective and adaptable. In the following summary the rules derived from the use of the formulas will be given, along with the more valid of empirical rules. For the derivation and statement of the formula in full, the student is referred to Petterssen's *Weather Analysis and Forecasting* (McGraw-Hill Book Co.), and Taylor's *Aeronautical Meteorology* (Pitman Publishing Corp.).

1. Movement of Pressure Systems. The movement of a pressure system (high or low) is strongly influenced by its pressure tendency. Lows travel at varying speeds as they deepen (pressure falls) and occlude. The high-pressure areas are also influenced by their deepening or filling (pressure rises) processes.

Lows

a. An occluded depression moves slowly, or is stationary.
b. All depressions move roughly parallel with the line joining the largest negative tendencies.
c. Depressions are stationary if the pressure changes are symmetrical with respect to the center.
d. Depressions tend to move in the direction of the upper winds at 10,000 ft. or above near the center of the depression.
e. Lows tend to follow the record of previous days (historical sequence). Lows tend to move toward regions

of greatest rainfall during the preceding 24 hours, also the areas of highest dew point and least wind velocities.

f. Secondary depressions tend to move in the direction of the circulation around their primary.

g. Depressions tend to move around large anticyclones in the same direction as the circulation of the anticyclonic winds.

h. Lows, on an average, travel about 600 miles in a 24-hour period. They are faster in winter than in the summer. They travel faster across the Northern States.

i. Northwest storms that move southeastward usually gather intensity upon recurving to the northward. At time of recurving their movement may be slow.

j. Lows with isobars closely crowded on the west and northwest generally move slowly to the east or southeast. Precipitation and high winds will be maintained unusually long in the western and northern sections.

k. Lows with closely crowded south and southeast quadrants tend to move rapidly northeastward. The weather may clear quickly after the passage of such a storm center.

l. A young cyclone will move parallel to the direction of the isobars in the warm sector.

m. The trajectory of a cyclone tends to curve from right to left after occlusion in the Northern Hemisphere.

* n. Until occlusion occurs, the rate of movement of a low increases.

o. After occlusion the speed of a low decreases until the maximum deepening of the center takes place.

p. A fast stable wave will move faster than an occluding low.

q. Cyclones are accelerated when the isallobaric profile is curved anticyclonically. They are retarded when the isallobaric profile is curved cyclonically.

Highs

a. An anticyclone separating successive depressions of a family will tend to move with the depressions.

b. An anticyclone that forms in an outbreak of polar air behind a cold front will move with the mass of cold air. This movement is generally toward lower altitudes.

c. Warm highs tend to move slowly or become stationary.

d. Highs move toward the greatest positive pressure tendencies.
e. Highs move faster in winter and have a greater tendency to turn southward while crossing the central valleys of the United States.

Pressure Centers in General

a. The velocity of a pressure center increases as the isallobaric gradient increases, and decreases as the isobaric gradient decreases.
b. When the pressure center is flat and the isallobaric gradient is strong the center will move rapidly.
c. Oblong pressure centers will generally move along the longer symmetry axis.
d. A pressure center moves normal to the isallobar running through its center.

2. Development of Disturbances—Deepening and Filling.
   a. Frontal waves may appear on sufficiently sharply defined and extended frontal occlusions.
   b. Newly formed disturbances are to be expected in the zone through which the main front passes.
   c. A region of negative tendencies in one place along a main front is one of the first signs of the appearance of a new cyclone. The development period of a young cyclone is about 24 hours.
   d. With the narrowing of the warm sector a disturbance deepens until occlusion takes place.
   e. If the air is conditionally unstable in the warm sector the cyclone will deepen.
   f. If fresh, cold air intrudes into a filling depression it will start to deepen again.
   g. Lows deepen with an increase in the instability of the surrounding air masses. In winter, a low will deepen when passing over the ocean from the land. In the summer, deepening will take place when the low passes from ocean to land.
   h. Newly formed frontal depressions deepen slowly at first, then rapidly until partly occluded after which deepening is slow.
   i. A fully occluded depression rarely deepens; it may fill up slowly or persist for several days.
   j. Old depressions may fill up rapidly when new deepening lows move into their circulation.

k. Two neighboring depressions seldom deepen at the same time.

l. Lows are deepening if the pressure is falling all around the center.

m. Lows are deepening if the rate of fall on one side is greater than the rate of rise on the other.

n. Lows are filling if pressure is rising all around the center.

o. Lows are filling if the rate of rise is greater on one side than the rate of fall on the other.

p. The depth of a low will not change if the tendency is zero all around the center, or if a fall on one side is balanced by a rise on the other.

q. Warm-sector cyclones deepen at a constant rate which is equal to the barometric tendency at the top of the warm sector.

r. Symmetrical-wave cyclones occlude with a velocity proportional to the warm-sector tendency.

s. Warm-sector cyclones deepen at an unaccelerated rate.

3. Evolution and Movement of Fronts.

a. Fronts tend to dissipate in anticyclonic regions (frontolysis).

b. If the cold air lies to the left of the general air flow the sharpness of a front increases.

c. If the cold air lies to the right of the general air flow the front will tend to dissipate.

d. Fronts with warmer air in the cold air mass to the north are short-lived.

e. A fast moving cold front soon dissipates.

f. Cold fronts upon approaching mountain ranges tend to intensify.

g. Fronts may form within an air mass if one portion of the air mass moves over a surface of contrasting thermal characteristics (secondary fronts).

h. Fronts may form within air masses where orographic phenomena cool the underlying air by precipitation from above.

i. High elevations tend to retard fronts. The higher the obstruction and the more shallow the height of the frontal surface the greater the retardation.

j. Fast-moving cold fronts will pass over low obstructions without marked deformation.

k. Warm fronts usually move more slowly than cold fronts.

l. The velocity of a front increases with an increase in the isallobaric tendency across the front and decreases with an increase in the barometric gradient difference across the front.

4. Pressure Temperature Indications.
   a. The barometer falls irregularly preceding a thunderstorm.
   b. Diurnal pressure changes must be considered in making pressure estimates.
   c. If pressure increases slowly after passage of a cold front, it may indicate convergent conditions and continued poor weather.
   d. Rapid rise in pressure and drop in temperature following a cold-front passage indicates clearing weather.
5. Temperature Forecasts.
   a. Cold waves occur when passing low is east of a high and if high has an oval form with the axis northeast-southwest. The cold wave will be in the southeast sector.
   b. The pseudo-adiabatic chart may be used as described elsewhere.
   c. Diurnal and seasonal variations must be considered.
   d. Air masses and their source regions must be considered. Stability of an air mass will influence heating.
   e. Allowance must be made for the condition of the atmosphere (clear or overcast) to account for radiation effects.
   f. Wind direction, precipitation and pressure systems all influence temperature. Frontal systems and their probable influence must be considered.
6. Some Empirical Rules.
   a. If a storm formed in the southwest is forced to the left of its normal track, another storm will immediately begin to develop in the southwest and it will be a sure rain producer.
   b. Storms that develop in the southwest and proceed normally are usually followed by clearing weather.
   c. Narrow, low-pressure troughs moving from the west have storm centers developing in extreme northern and southern ends.
   d. Wide, low-pressure troughs often show the wide development of an extensive storm area. This is especially true if the wide intervening area between highs shows relatively high temperatures.
   e. When the northern end of a trough moves eastward

at a greater rate than the southern end the weather will remain unsettled in the southwest and south. A storm is likely to form southwest of the following high.

f. If the southern end of a trough moves faster than the northern end, settled weather will follow.

g. East of the Rocky Mountains, a storm which moves to the left of its normal track will increase in intensity.

h. If there are marked changes in temperature in the northwest or southeast quadrants an increase in the storm's intensity can be expected.

i. If there is a high-pressure area over the southeast and a cold wave develops in the northwest, a storm will develop in the southwest and precipitation will be general.

j. Lows that pass over the Gulf of Mexico deepen and increase in storm intensity. Moist southeast winds from off the south Atlantic will intensify lows moving up the Atlantic seaboard from south to north.

k. Highs which separate a series of lows tend to go southward.

l. High-pressure areas have a tendency to turn south during the winter in the central valleys of the United States.

m. Highs, in general, move with the same speed and in the same direction as the frontal cyclones.

n. A gradual increase in temperature accompanying southerly wind which precedes the appearance of a front is generally an indication of possible stormy weather.

D. Local Forecasts.

1. Local Factors to Be Considered. In making a forecast the following local factors must be given careful consideration.

a. Wind.

(1) When the pressure gradient is the same, winds from the sea will be stronger than winds from the land.

(2) In forecasting winds the local sheltering effects of high ground to the windward must be considered.

(3) Deviating effect of hills on wind direction.

(4) Katabatic effects.

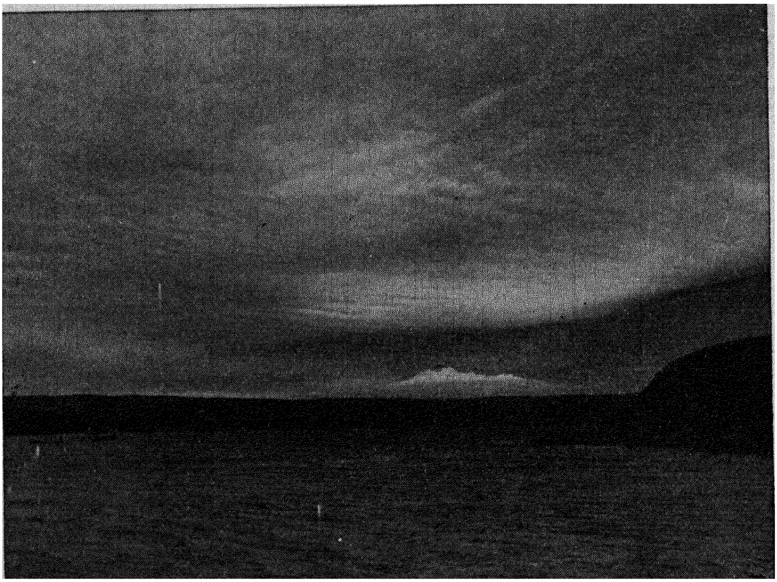
(5) Funnel effects.

(6) Turbulence variations due to ground contour.

(7) Diurnal land and sea breezes.

b. Precipitation.
   (1) Intensification of general rain by orography.
   (2) Tendency for thunderstorms to favor certain regions.
   (3) Coastal effects resulting in instability showers.

c. Clouds.
   (1) At the coast, the effect of wind direction on turbulence or convection clouds. (Fig. 116)
   (2) Lowering of cloud base to the windward and clearance to the lee of high ground.
   (3) Turbulence differences and their effect on low clouds.
   (4) Orographic clouds over high ground. (Fig. 116)



Courtesy Lt.(j.g.) J. Dungan, U.S.N.

Fig. 116. Coastal clouds and orographic effects.

Altostratus, altocumulus (in foreground) and stratus (around base of mountain). Worthy of particular notice is the elevation of the altostratus cloud sheet over hill in the right foreground. This is a fine example of an orographic effect.

   (5) Effect of differences between land and sea.
   (6) Smoke effects as varied by wind direction.
   (7) Nature of the ground as it affects radiation fog.
   (8) The effect of local winds and clouds on the formation of radiation fog.

d. Temperature.
   (1) Low-radiation temperatures in valleys.
   (2) Effect of altitude.
   (3) Land and sea differences.
   (4) Radiation as affected by clouds.
   (5) Possible föhn effects of high ground to the windward.

2. Indications of Clouds.
   a. Cirrus Clouds.
      (1) Cirrus clouds arranged in bands indicate approaching warm front.
      (2) If these clouds thicken and an altostratus system appears, it is a good indication of an approaching warm front or occlusion and stormy weather within 24 hours.
   b. Cumulus Clouds.
      (1) If cumulus clouds appear early in the morning during the summer, showers may be expected during the afternoon.
      (2) If these cumulus clouds do not appear until late in the morning, showers will be late in the afternoon and light.
      (3) If the vertical development of such cumulus clouds is limited, little activity can be expected (fair weather cumulus).
      (4) Rain will rarely fall from cumulus clouds until the upper portions of the clouds have reached the freezing level. This state is indicated by the visible formation of a filmy "ice mantel." This condition is known as the *ice-crystal stage*.

3. Indications of the Wind.
   a. If the wind exhibits a tendency to back into southerly directions, it indicates the approach of a cold front. An increase in velocity usually occurs with this sign.
   b. An indication of the intensity of the coming cold front can usually be obtained from the velocity of the wind, and the temperature and humidity of the air.
   c. In northern latitudes the wind will generally shift from south or southwest to north or northwest with the passage of cold fronts.
   d. With the passage of warm fronts in northern latitudes the wind shift is from southeast or south to south or southwest.

4. Indications of Possible Thunderstorms.
   a. Highly humid, warm weather, where dew point exceeds 60° F. and temperature exceeds 80° F. during the middle of the forenoon with fairly light surface winds, indicate possible thunderstorms in the afternoon. These indications are particularly reliable in the Gulf Coast regions.
   b. Cumulus clouds of high vertical development, formed early in the morning, are indicative of instability and thunderstorms.
   c. A thick opalescent, bluish haze, along with preceding conditions during the late forenoon, indicate thunderstorms.
   d. Occurrence of altocumulus castellatus in the late morning or early afternoon indicates possibility of thunderstorms since this cloud type shows that there is marked instability in the intermediate levels. The appearance of the cloud gives several hours' warning. (Fig. 117)

Fig. 117. Altocumulus castellatus clouds (from International Cloud Atlas).

This cloud type indicates unstable conditions and probable thunderstorm activity during the day.

e. Mammatocumulus clouds indicate severe turbulence and hail, and the imminent possibility of a thunderstorm. (Fig. 118)

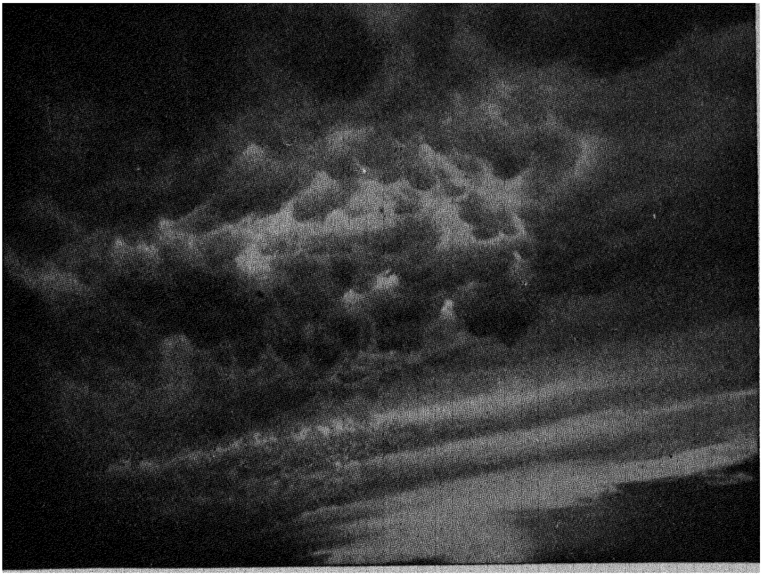


Fig. 118. Mammatocumulus clouds.

Mammatocumulus indicate very unstable conditions. These clouds are associated with thunderstorm activity.

E. Local Weather Signs.

1. Difficulties. Local sky signs are applicable only where strong local influences do not interfere.
2. Sky Signs.
   a. Red sky at night indicates fair weather.
   b. Grey sky in the morning indicates fair weather.
   c. Red, lurid sky in the morning indicates bad weather; probable rain or snow.
   d. Light, bright blue sky indicates fair weather.
   e. Bright yellow sunset indicates wind.
   f. Pale yellow sunset indicates rain.
   g. Cirrus clouds, thickening into heavier forms in rapid succession, indicate stormy weather.
   h. Banded cirrus indicates stormy weather in 24 hours.
   i. Mammatocumulus indicates imminent thunderstorm.
   j. Long roll cloud indicates line squall.

k. Towering cumulus with ice mantel indicates showers, possible thunderstorm.

l. Cumulonimbus with high vertical development indicates thunderstorm.

TEST QUESTIONS ON WEATHER-MAP ANALYSIS AND FORECASTING

1. The figures 998 entered on the synoptic map for pressure indicate (a) 998 mb, (b) 999.8 mb, (c) 1098.8 mb, (d) 999.98 mb.

1. ________

2. Isobars should first be drawn in solid (a) at the fronts, (b) in the warm sector, (c) in the cold air mass. 2. ________

3. In the United States, it is a good practice to start drawing the isobars in the (a) Rocky Mountains, (b) central valleys, (c) east coast, (d) west coast. 3. ________

4. The standard interval between consecutive isobars is usually (a) 3 mb, (b) 5 mb, (c) 10 mb, (d) 2 mb, (e) 1 mb. 4. ________

5. Two isobars having the same value and occurring side by side indicate a (a) low, (b) occlusion, (c) warm front, (d) col.

5. ________

6. Over the land the winds flow across the isobars at an angle of about (a) 10°, (b) 50°, (c) 20°, (d) 35°, (e) 75°. 6. ________

7. The pressure around an isobar (a) may change from one side to the other, (b) always remain higher on one side and lower on the other, (c) may be the same on each side. 7. ________

8. Strong winds will flow along (a) smooth isobars, (b) irregular isobars. 8. ________

9. Irregularities of the isobars (a) are never valid, (b) are always valid, (c) may sometimes be valid. 9. ________

10. Isobars (a) will, (b) will never, (c) sometimes, cross.

10. ________

11. Isobars may (a) never, (b) always, (c) sometimes, be left open.

11. ________

12. Personal errors in pressure may be recognized (a) by comparison with a previous map, (b) as inconsistent with the precipitation, (c) as inconsistent with the wind direction. 12. ________

13. Isobars should be (a) drawn smoothly through fronts, (b) discontinuous at the front, (c) smoothed at the front. 13. ________

14. Errors of pressure from ship reports are usually (a) errors of reduction to sea level, (b) personal errors, (c) errors of position.

14. ________

15. Indicate the method of identifying cold fronts on printed charts.
15. ________

16. An upper-air occluded front is indicated as (a) alternate red and blue lines, (b) dotted lines, (c) broken purple lines, (d) broken blue lines.
16. ________

17. The weather to be expected at any front depends (a) entirely on the frontal type, (b) upon the nature of the interacting air masses.
17. ________

18. A general description of the pressure distribution and position of fronts is known as (a) area forecast, (b) local forecast, (c) general inference, (d) route forecast. 18. ________

19. Deepening refers to (a) a pressure rise, (b) an increase in temperature, (c) a decrease in the wind, (d) a fall in the pressure, (e) the genesis of an anticyclone. 19. ________

20. Filling refers to (a) a pressure rise, (b) an increase in temperature, (c) a decrease in the wind, (d) fall in the pressure, (e) the genesis of an anticyclone. 20. ________

21. Cyclogenesis refers to ________.

22. Frontogenesis means ________

23. Frontolysis is ________

24. Anticyclolysis is the ________

25. Cyclolysis is ________

26. Anticyclogenesis refers to ________

27. Depressions tend to move roughly parallel to the line joining the largest (a) positive, (b) negative, tendencies. 27. ________

28. Lows travel an average of about (a) 100, (b) 200, (c) 300, (d) 400, (e) 500, (f) 600, miles in 24 hours. 28. ________

29. Before occlusion a cyclone (a) accelerates, (b) decelerates.
29. ________

30. The velocity of a pressure center (a) increases, (b) decreases, as the isallobaric gradient increases. 30. ________

31. Oblong pressure centers will tend to move along (a) the longer, (b) the shorter, symmetry axis. 31. ________

32. A region of negative pressure and converging winds along a front indicates (a) frontolysis, (b) anticyclolysis, (c) anticyclogenesis, (d) frontogenesis, (e) anabatism. 32. ________

33. Fronts entering anticyclonic regions tend toward (a) anticyclolysis, (b) anticyclogenesis, (c) frontolysis, (d) frontogenesis, (e) katabatism.
33. ________

34. Warm-sector cyclones deepen at a constant rate which is equal to the barometric tendency at (a) top, (b) middle, (c) bottom, of the warm sector. 34. ________

35. Cold fronts (a) dissipate, (b) remain the same, (c) intensify, upon approaching mountain ranges. 35. ____________

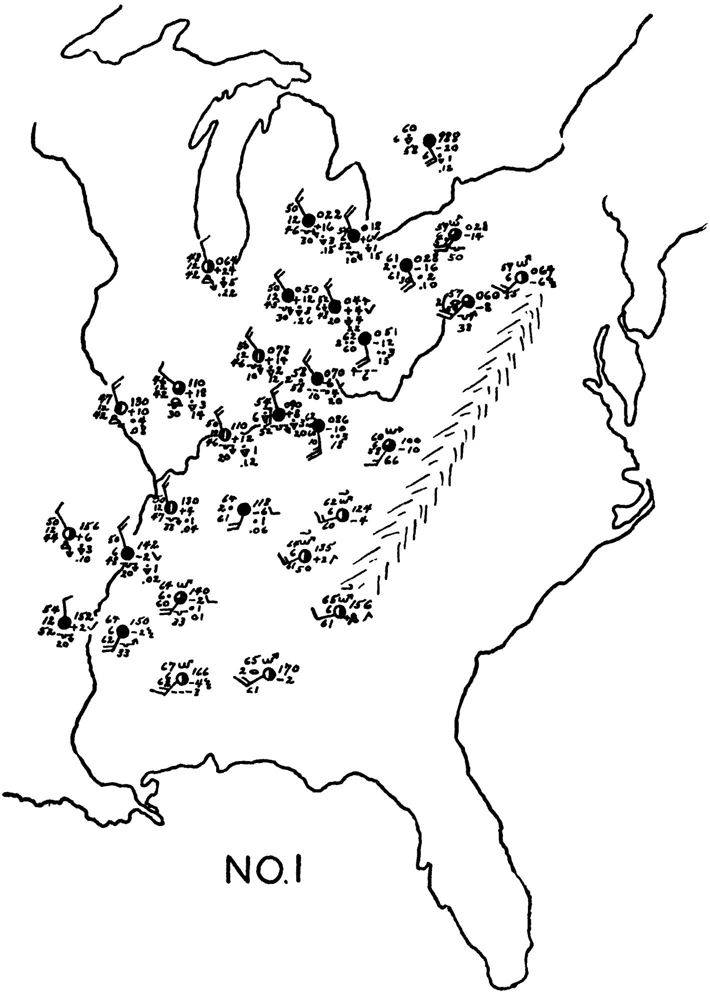
36. The barometer (a) falls steadily, (b) falls irregularly, (c) rises steadily, (d) rises irregularly, preceding a thunderstorm. 36. ____________

37. Southeast winds along the Atlantic Coast tend to (a) dissipate, (b) not influence, (c) deepen, lows. 37. ____________

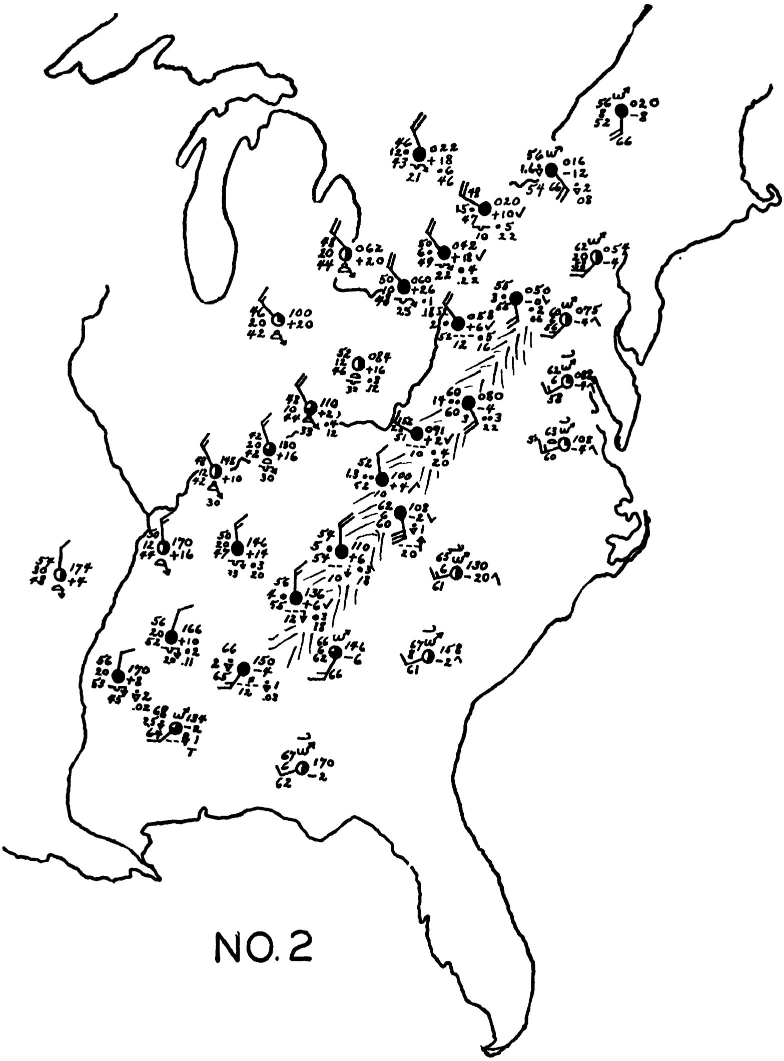
38. If the air in a warm sector is unstable the depression will tend to (a) deepen, (b) fill, (c) undergo frontolysis. 38. ____________

39. ____________ may appear on sufficiently sharply defined and extended frontal occlusions. 39. ____________

40. The development period of a young cyclone averages about (a) 12, (b) 24, (c) 36, (d) 48, hours. 40. ____________



Sketch in isobars, fronts and pressure systems and make a series of six-hour forecasts. Verify forecast on successive maps.



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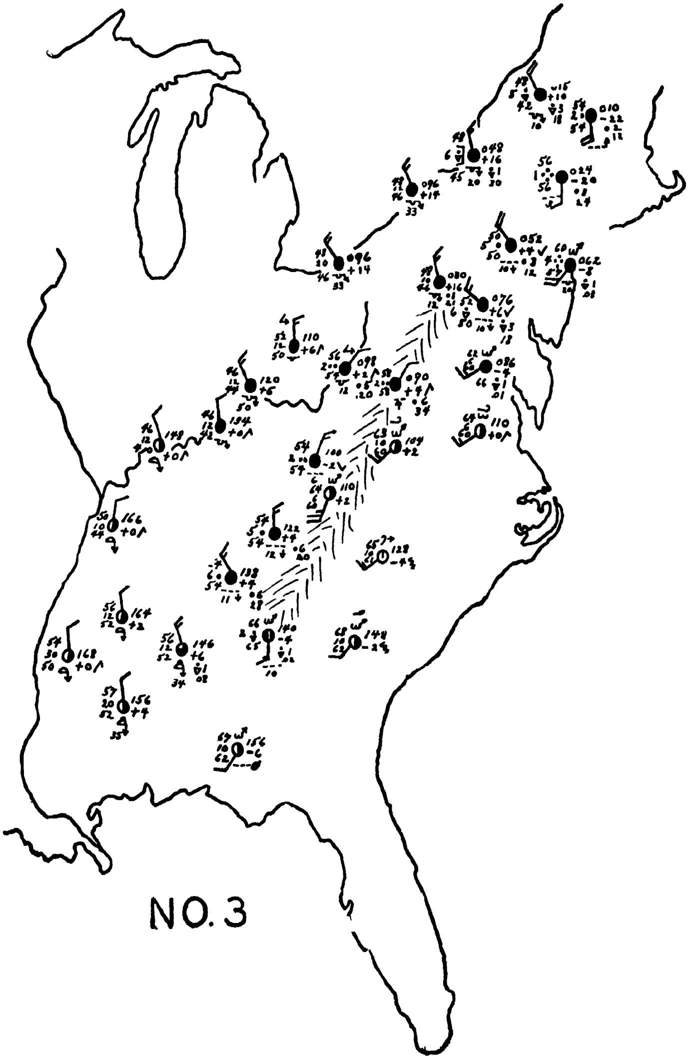

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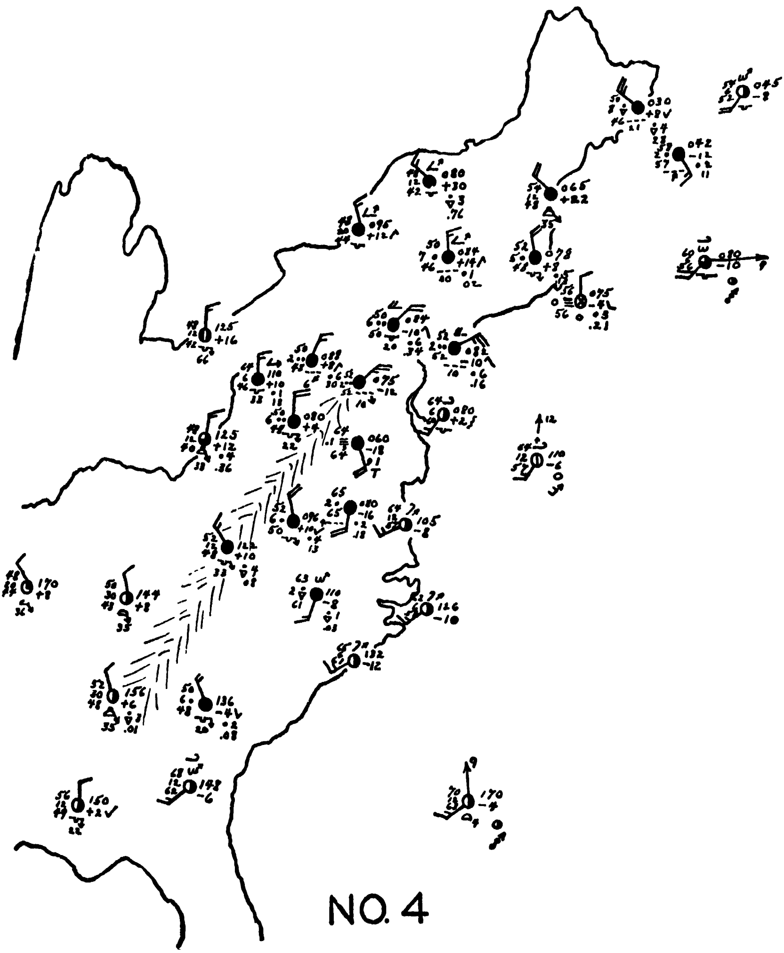

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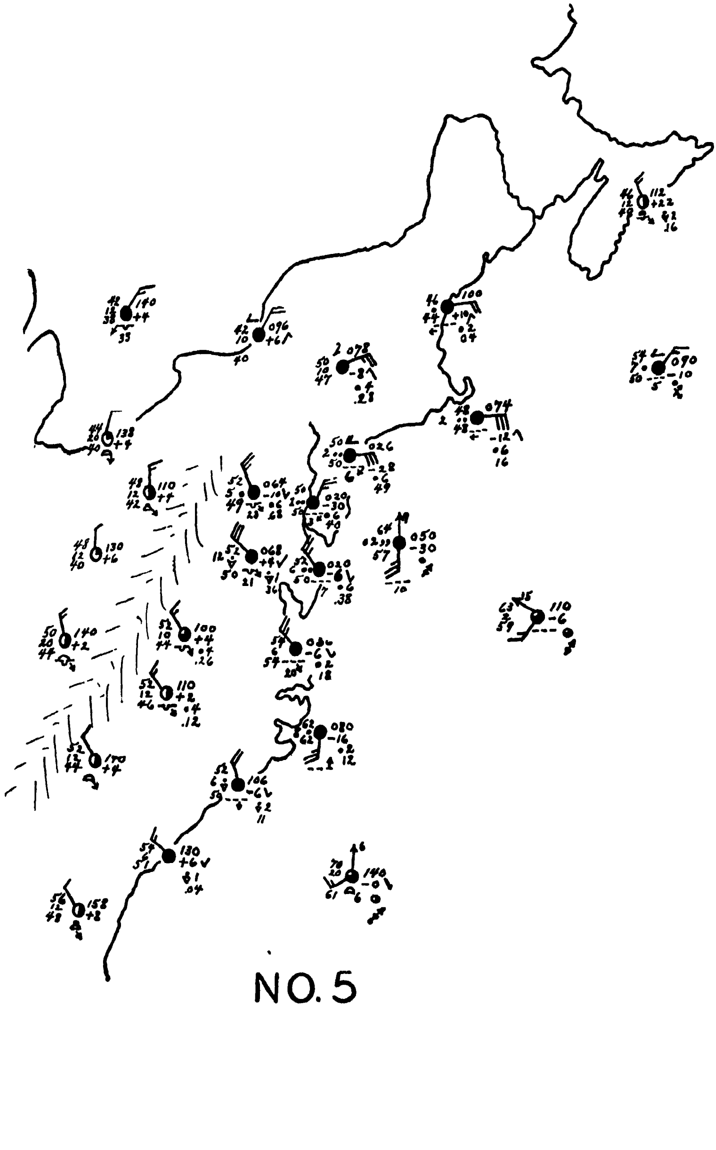


NO. 5

QUESTIONS FOR EXAMINATION AND STUDY

The following 500 questions have been prepared to assist the student to review and evaluate his knowledge of the subject. A large number of questions asked in many different ways prevents the acquisition of a narrow, limited understanding of the science. All of the questions, with the possible exception of a few of the last of each group, can be answered on the basis of material included in this book. A limited number of advanced questions are included to encourage the student to do some collateral reading from advanced texts. It should be remembered, however, that most of the questions can be answered without the necessity of obtaining outside reference although, in many cases, the answer is not immediately evident. The serious student who makes an earnest effort to find the solution of all the problems in this chapter will find that his study is amply rewarded by the well-rounded mastery of the practical aspects of the science that he will acquire.

I. BASIC CONCEPTS

A. *True* or *False*

1. An apriori assumption is made that the atmosphere will obey physical laws in deducing physical meteorological principles.
2. The synoptic meteorologist seeks to explain on the basis of rigid physical principles the more common phenomena observed in the atmosphere.
3. Climate implies the summation of weather conditions over a period of years.
4. The air at sea level is at a lesser pressure than the air at 2000 ft.
5. It is believed that at about 11 km the various gases are distributed according to molecular weight.
6. The dividing line between the stratosphere and troposphere is called the ionosphere.
7. The tropopause is colder in the summer than in the winter at 80° N. Lat.
8. The amount of carbon dioxide and water vapor in the air is variable.
9. Density is defined as volume per unit mass.
10. One half of the entire mass of the atmosphere is below 3.6 miles.
11. A kilometer is more than a mile.
12. The isothermal zone is found at a greater height in winter than in summer.

B. *Multiple Choice* or *Completion*

1. The single factor which is the basis of all weather changes is the (a) wind (b) sun (c) pressure (d) earth's rotation.
2. Atmospheric pressure decreases 1/30 of its value at any given moderate elevation with an increase in height of (a) 100 meters (b) 1000 meters (c) 900 ft. (d) 300 ft.
3. The greatest mass of the atmosphere is found in the ———.
4. The level at which the temperature drop with height stops is known as the ———.

5. The tropopause is lowest at ——— latitude.
6. The region in which the temperature, on the average, decreases with height is called the ———.
7. The horizontal distance at which objects can be identified is called ———.
8. ——— is the summation of weather conditions over a series of years.
9. The division between the troposphere and the stratosphere is called the ———.
10. ——— is the study of weather conditions over a large area at a given instant.
11. The level of constant density is coincident with the ——— region.
12. The ——— gases exist in nearly the same proportion at all altitudes.

C. *Study Questions*

1. Define "meteorology."
2. Name the elements (9) which constitute the atmosphere. Which one is predominant?
3. What is the height of the atmosphere? Discuss.
4. Define "weather"; "climate." What are 6 important weather elements?
5. Define troposphere; tropopause; stratosphere.
6. What is the ozone layer? Discuss.
7. Discuss the ionized layers in the atmosphere.

II. ATMOSPHERIC THERMAL RELATIONSHIPS

A. *True* or *False*

1. All of the energy received by the earth from the sun is eventually reradiated to space.
2. A micron is 1/100 of a millimeter.
3. The chemical rays are selectively absorbed by the ozone layer.
4. 0° Centigrade equals 273° Absolute.
5. Radiation is an adiabatic process.
6. Outgoing terrestrial radiation is of the short-wave type.
7. The "permanent" gases of the earth are nitrogen, oxygen, and water vapor.
8. The chief method by which heat is transferred within the atmosphere is by radiation.
9. Lines of equal rainfall are called isotherms.
10. To change Centigrade to Fahrenheit, add 32° and take 5/9 of the result.
11. The most heat is received from the sun at noon.
12. Violet light is found in the long-wave-length region of the spectrum.
13. At the equator, the incoming solar radiation exceeds the radiation lost to space by the earth.
14. Land and water surfaces absorb and radiate heat at the same rate.
15. A superadiabatic lapse rate is highly unstable.
16. Air is a poor conductor of heat.
17. At all heights in the troposphere, the amount of radiation absorbed of the outgoing terrestrial kind is greater than the solar radiation absorption.
18. Inversions may be caused by turbulence.
19. The smoke in the atmosphere absorbs more radiant energy than the water vapor in the atmosphere.
20. A line passing through the center of a belt of high temperature which exists near the geographical equator is called the equinox.
21. The changes, in the course of an average day, of the magnitude of a meteorological element are known as seasonal variation.
22. Dry air is exceedingly diathermanous.
23. The normal dry-adiabatic lapse rate is 1° C. per 100 meters.

24. The dry-adiabatic lapse rate is not applicable to air that has 50% relative humidity.
25. Moist air is heavier than dry air.
26. Another term that might be used for adiabatic is isentropic.
27. If the maximum thermometer is set and left in a place for a year, it will record the highest temperature of the year reached at that place.
28. Horizontally converging moist air in the summer tends to make the lapse rate more stable.
29. The fluid in a maximum thermometer is alcohol.
30. If the lapse rate was 2° C. per 100 meters, the air would not be gusty.

B. *Multiple Choice* or *Completion*

1. The vernal equinox falls on (Dec. 21, June 21, March 21, Sept. 23).
2. In warm and very moist air masses, strong vertical motions may occur even with only (weak, strong, normal, moderately strong, superadiabatic) lapse rates.
3. An increase in the depth of the ozone layer in the stratosphere would cause a consequent (increase, decrease) in surface temperature.
4. The most important agency for the transfer of heat in the free atmosphere is (molecular conduction, eddy transfer, radiation, atomic conduction).
5. The dry-adiabatic lapse rate is (0.6° C. per 100 meters, 3.2° F. per 1000 ft., 1° C. per 100 meters, 3.4° C. per 100 meters).
6. Most of the sun's radiation is absorbed by (nitrogen of the air, water vapor in the atmosphere, oxygen in the atmosphere, argon).
7. A stable lapse rate is one which is (greater than, less than, the same as) the dry-adiabatic lapse rate.
8. Transfer of heat by the bodily movement of the substance containing the heat is known as (conduction, convection, radiation, insolation).
9. A temperature inversion is defined as ———.
10. Superadiabatic lapse rate causes ———.
11. The passage of heat by the means of molecular motions is called ———.
12. The most important agency for the transfer of heat in the free atmosphere is ———.
13. The transfer of energy without the necessity of a material media is called ———.
14. ——— is the most effective process for cooling air.
15. The lapse rate is defined as ———.
16. When the atmosphere is clear and dry, the ground cools quickly by the process of ———.
17. About ——— of the energy incident at the top of the atmosphere is reflected or diffused back into space.
18. ——— of the incident radiation is absorbed by H_2O vapor in the atmosphere and ——— by permanent gases, dust and clouds.
19. When the lapse rate exceeds 3.42° C. per 100 meters the atmosphere is said to be ———.
20. Because, throughout the ages, the earth neither becomes progressively hotter nor colder it is believed that there is what is known as a ——— of the atmosphere.
21. When heat is carried by currents set up in a fluid, the process is called ———.
22. If the lapse rate is the same as the rate for adiabatic changes in dry air, it is called the ———.
23. Continental effects are more pronounced in the ——— Hemisphere than in the ——— Hemisphere.
24. The average decrease of temperature with height over the entire earth is approximately ———.
25. At low temperatures the moist-adiabatic rate is nearly equal to ———.
26. The less the lapse rate the more ——— is the air.
27. The solar constant is ——— cal. per square centimeter per minute.

28. The dry-adiabatic rate is ———.
29. The belt of maximum insolation is called the ———.
30. In summer, the isotherms bend ——— over the continents.
31. Due to the fact that the water vapor of the air transmits short waves better than long waves, the presence of water vapor in the lower levels of the atmosphere gives rise to the phenomenon known as ———.
32. ——— during the day and inversions at night occur during cloudless summer days.
33. In low latitudes ——— energy is lost to space by radiation than is received.
34. The atmosphere transmits certain wave lengths better than others. This property is known as ———.
35. Identify the following percentages in relation to the depletion of solar energy in the atmosphere: 43%; 12%; 5%; 19%.
36. The amount of heat necessary to raise the temperature of one gram of water one degree Centigrade is known as a/an ———.
37. When reference is made to the amount of thermal energy, without regard to the level, ——— is the concept referred to.
38. The amount of heat necessary to raise a unit amount of a substance a unit amount is the ——— of the substance.
39. The ——— is the amount of heat necessary to raise one pound of water one degree Fahrenheit.
40. A μ is ——— of a millimeter.
41. The above unit is used to measure ———.
42. Three scales are now commonly used for measuring temperature: namely, Centigrade, Fahrenheit and ———.
43. The scale divisions on the Centigrade and ——— are the same.
44. A one-degree division on the Centigrade scale is equal to ———.
45. The reference points on the Centigrade scale are ——— and ———.
46. The process by which one form of energy is changed to another form is called ———.
47. Identify $\frac{1}{2,000,000,000}$.
48. H_2O vapor, carbon dioxide, ozone, and solid impurities are all classified together as ———.

C. *Study Questions*

Identify or complete the following:

1. 0.38μ to 0.78μ ____________
2. 186,000 miles per second ____________
3. 300,000 kilometers per second ____________
4. —40° ____________
5. +273° A. ____________
6. —459.4° F. ____________
7. 0°A. ____________
8. F — 32 × 5/9 ____________
9. .78μ to 10μ ____________
10. .0132μ to .38μ ____________
11. .2μ to 3μ ____________
12. +14° F. to C. = ____________
13. +50° C. to F. = ____________
14. +212° F. to F.A. = ____________
15. —94° F. to C. = ____________
16. Illustrate by diagrams the conditions especially favorable for convectional instability.
17. (a) Define an adiabatic process. (b) The temperature is increased by compression when air flows downhill, assuming adiabatic conditions; does this gain in temperature mean a net gain in heat?
18. Illustrate graphically the stability types.

19. List the three methods of heat transfer, and give their approximate magnitude.
20. Find the final temperature of a mixture of 400 grams of iron at 20° C., 500 grams of water vapor at 120° C., 1000 grams of ice at —5° C. (Sp. ht. ice — 0.5, steam = 0.5, iron = 0.135, water = 1).
21. What is Absolute zero? How is it determined?
22. When was the thermometer invented, and by whom? The barometer?
23. What is heat?
24. What thermometric scales are in general use? Describe.
25. What are the requirements for an accurate thermometer?
26. Describe the maximum thermometer.
27. Describe the minimum thermometer.
28. What is radiant energy? Radiation?
29. Define, and briefly discuss, the following terms: transmission, absorption, reflection
30. Where does the atmosphere get its heat? What is the name given to this heat?
31. Define calorie. What is the solar constant?
32. Does the earth receive more insolation in January or July?
33. Discuss conduction.
34. Discuss convection in the air.
35. What is meant by the term adiabatic? What is the adiabatic lapse rate for dry air?
36. What is meant by moist or saturated adiabatic? Explain.
37. Define potential temperature. Explain. Define and explain equivalent potential temperature.
38. What is meant by the term "lapse rate"? Is the lapse rate always the same as the dry or wet adiabatic?
39. What is a temperature inversion? How are inversions formed?
40. What does the term stability mean with respect to lapse rates? Illustrate a stable lapse rate.
41. What is the general rule for determining stability?
42. What is instability? Illustrate an unstable lapse rate.
43. What is meant by conditional instability? Explain.

III. HUMIDITY, TEMPERATURE AND PRESSURE RELATIONSHIPS

A. *True* or *False*

1. Water vapor is an invisible gas.
2. Sublimation is the process of changing from a vapor to a liquid.
3. 40 calories per gram is necessary to melt ice.
4. A volume of moist air is heavier than an equal volume of dry air.
5. Relative humidity is less conservative than specific humidity.
6. The water vapor content of the atmosphere varies inversely with the temperature.
7. The virtual temperature of a parcel of air is always less than the actual temperature.
8. The dew-point temperature and the temperature of the condensation level in adiabatic cooling are synonymous.
9. The only air-mass property which remains conservative before and after condensation is the potential temperature.
10. Specific humidity is conservative with respect to dry adiabatic changes.
11. Potential temperature and the water content per unit mass are independent of adiabatic processes in the absence of condensation or evaporation.
12. A mackerel sky is a sky covered by cirrostratus.
13. Clouds having projecting points or wedges like anvils are usually cumulus castellatus.
14. If potential temperature decreases with height, the air is convectively unstable.

15. The dry-bulb thermometer of a psychrometer always reads lower than the wet-bulb thermometer.
16. When the air is saturated, wet and dry thermometers give the same readings.
17. The virtual temperature is the temperature air would have if all the heat contained latent in the water vapor were realized.
18. The fact that the human hair will measure directly the relative humidity of the air is a principle made use of in the barograph.

B. *Multiple Choice* or *Completion*

1. The definition of (relative humidity, absolute humidity, mixing ratio. specific humidity) is weight of water per unit weight of moist air.
2. The temperature a parcel of air would have if it were raised or lowered dry-adiabatically to the 1000-mb level is known as (equivalent temperature, potential temperature, dew-point temperature, equivalent potential temperature).
3. The cloud type which is conducive to the formation of hail is the (cumulonimbus, altocumulus, stratus, cirrus).
4. To change a gram of water to vapor, it is necessary to (add 80 cal., add 620 cal, subtract 540 cal., add 540 cal.).
5. When one gram of water changes to ice ——— cal. are liberated.
6. The ratio of the amount of water vapor contained in a volume of air to its capacity, and expressed as a percentage, is the ———.
7. The mass of water vapor in a mass of moist air is known as ———.
8. The temperature of an air parcel at 1000-mb pressure is called ———.
9. The temperature at which a given volume of dry air would have the same density as an equal volume of moist air is called the ——— temperature.
10. The amount of heat necessary to raise one gram of water one degree Centigrade is called a ———.
11. When the vapor pressure of a liquid is equal to the atmospheric pressure ——— takes place.
12. All hygroscopic nuclei absorb ——— from the air.
13. Since ten calories are needed to raise the temperature of one gram of ice 20 degrees its specific heat must be about ———.
14. The mass of H_2O vapor in a unit mass of dry air is called ———.
15. If pressure is constant, the temperature of air after all heat of condensation has been realized is called ———.
16. The heat energy required to change water to a vapor is called ———.
17. The number of calories liberated per gram by the condensation of water vapor is known as ———.
18. The temperature to which unsaturated air must be cooled to reach saturation is called its ———.
19. When a substance changes directly from a vapor to a solid ——— has taken place.
20. From a given temperature and pressure, go up the dry adiabat to saturation and then down the moist adiabat to same pressure. Reading off this temperature gives the ———.
21-25. Choose the statement in Column B which most nearly describes the statement in Column A.

Column A	*Column B*
1. sublimation	a. air cooled below its dew point.
2. hail	b. feathery deposit of ice from freezing fog.
3. water vapor	c. advection type.
4. sleet	d. change from gaseous to solid state directly.
5. rime	e. radiation type.
6. sea salt	f. convection type.
7. ground fog	g. falls from cumulonimbus clouds.

Column A	*Column B*
8. dew	h. frozen raindrops.
9. snow	i. glaze.
10. sea fog	j. invisible gas.
	k. hygroscopic nuclei.
	l. condensation occurring in air after temperature falls below 32° F.

C. *Study Questions*

1. How does the air obtain water vapor? What is the percentage of water vapor in very dry air and in moist air?
2. Discuss the presence of organic and inorganic particles in the air.
3. What is latent heat of vaporization? Explain.
4. What is meant by vapor pressure? How is it expressed?
5. What is dew point, and how is it determined?
6. What is meant by "condensation"? Explain.
7. (a) What is "latent heat of condensation"? (b) Explain how lapse rate of a sample of air is affected by condensation. (c) What is "super-saturation"?
8. (a) Define absolute humidity. (b) Can the value of absolute humidity change and how?
9. (a) Define relative humidity. (b) How is relative humidity expressed? (c) Can the value of relative humidity be changed and how?
10. Define specific humidity. (b) How is specific humidity expressed? (c) Can this value be changed?
11. Discuss the formation of dew.
12. Discuss the formation of frost.
13. What is rain? Discuss the formation of rain.
14. What is snow, and how is it formed?
15. Discuss the formation of hail.
16. Define and discuss sleet, graupel and glaze.
17. At 32° F. a cubic foot of air contains two grains of water vapor. Its capacity at that temperature is 2.113 grains. Its relative humidity equals ———.
18. Name six products of condensation and give a short definition of each.
19. The latent heat of fusion of 6.75 grams of ice is about 540 cal.
20. What is an iridescent cloud? What is a noctilucent cloud?
21. Draw a temperature-height curve and dew-point curve for a stratus cloud formation with a temperature inversion above the cloud top.

IV. *PRESSURE PHENOMENA AND WINDS*

A. *True* or *False*

1. A warm, dry wind which blows down the slopes on the leeward side of a ridge of mountains is known as katabatic.
2. In the Northern Hemisphere, with one's face to the wind, the higher pressure is on the righthand side.
3. The belts of calms, light winds and fine clear weather between the trade-wind belts and the prevailing westerly winds of higher latitudes are called the doldrums.
4. Gustiness and turbulence are important factors which cause the air to be bumpy.
5. Air pockets will naturally exist on the windward sides of hills, buildings or other obstructions.
6. Antitrades are modified by local disturbances.
7. In general, one finds high-pressure areas over land in winter.
8. Normal atmospheric pressure is 1018.2 mb.
9. The thermal equator crosses the geographical equator once every 365 days.

10. Charles' law states that the volume of a gas is directly proportional to the Absolute temperature.
11. A local wind is called anabatic if it is caused by the convection of heated air.
12. Winds aloft have lower velocities than winds on the ground.
13. Pressure can be expressed in tons per square meter.
14. To measure the gustiness of the air, it is better to use the Dines pressure-tube anemograph than the Robinson cup-type anemometer.
15. Vertical mixing brought about by gustiness tends to increase the speed of the surface winds during the day.
16. The winds at the equator and poles are from the west.
17. Boyle's law states that as the pressure on a gas decreases, the volume likewise decreases.
18. The barograph is an instrument for measuring pressure.
19. 29.92 in. corresponds to about 750 mm.
20. One cubic foot of air weighs about .08 lb.
21. The horse latitudes are belts of low pressure.
22. If the bore of a mercurial barometer is one square centimeter, 30.00 in. of mercury will weigh as much as a column of air one centimeter square and extending from the level of the mercury in the cistern to the top of the atmosphere.
23. The prevailing westerlies are the most important influence governing the climate of Hawaii.
24. One bar equals approximately 1,013,200 dynes per square centimeter.
25. A hot wind occurring in the warm sector of a passing depression, and heated by moving over hot and dry land areas, is generally known as a Sirocco.

B. *Multiple Choice* and *Completion*

1. The winds blow at an angle to the isobars on land because of (the Coriolis force, frictional influence, the gradient wind, high pressure at the ground).
2. The winds that blow from the horse latitudes toward the belt of low pressure at the polar circles are known as (trade winds, doldrums, prevailing westerlies, prevailing easterlies).
3. If the pressure is 1000 mb at the surface, at an altitude of 2000 ft. the pressure is (1033.3 mb, 966.7 mb, 920.2 mb, 934.5 mb).
4. The expansion of the atmosphere during the daylight and its contraction at night give rise to a change in the pressure known as (radiation, diurnal variation, sublimation, precipitation).
5. Winds returning from the low at the equator to the high at 35° N. Lat. are called ———.
6. The law which states that at constant temperature the volume of a gas varies inversely with the pressure is known as ———.
7. ——— makes the wind blow at an angle to the isobars.
8. The relatively warm westerlies meet the cold polar easterlies along an irregular shifting boundary which is known as the ———.
9. Subsidence occurs in the primary circulation at the poles and the ———.
10. A seasonal wind called the monsoon blows toward the sea during the ———.
11. The low-pressure belt of calm winds at the equator are known as the ———.
12. A ——— is never due entirely to mechanical effects, but is associated with variations in other meteorological factors.
13. Normal atmospheric pressure at sea level and 45° latitude is ——— mb.
14. Change in pressure per unit change in distance is known as ———.
15. The steady moderate winds blowing out of the horse latitudes toward the equator are called ——— winds.
16. The mistral is a ——— wind.
17. Moist, cold winds blowing down slopes are known as ——— winds.

18. A ——— wind is a wind which blows along curved isobars.
19. The ——— force is the deflecting force due to the earth's rotation.
20. One belt of calms is at the equator, the other is at the ———.
21. Wind which blows along straight, parallel isobars is known as ——— wind.
22. The westerlies are stronger in the ——— Hemisphere.
23. The ——— are high-pressure belts found in the Northern and Southern Hemispheres.
24. The depth of the trades is greatest at any given place during the ———.
25. ——— start to blow inland between two and three P.M.
26. ——— law states that winds will back in the Southern Hemisphere.
27. At the ———, the deflective force vanishes
28. Winds on the lee side of a mountain that have been heated by condensation and subsidence are called ——— winds.
29. Modifications in the primary circulation constitute what is known as ——— circulation.
30. The difference between maximum gusts and lulls divided by the mean wind, and expressed as a percentage, is called the ———.
31. Momentary deviations in the mean wind are called ———.
32. Winds that blow upslope during the day are called ——— winds.
33. Such winds are usually lacking in intensity because of ———.
34. Of the forces which effect gradient wind only ——— is independently variable.
35. In mountain passes, thermals occur along the sides during the ———

C. *Study Questions*

1. What is Boyle's law?
2. What is the law of Charles and Gay-Lussac?
3. What is the density of the air at sea level? How determined?
4. (a) Name the scales in use on barometers. (b) Define bar; millibar; dyne.
5. (a) Discuss the change in pressure with altitude. (b) Describe an altimeter.
6. Define pressure gradient.
7. Discuss land and sea breezes.
8. What are katabatic winds?
9. What is a monsoon?
10. What are the doldrums, and where are they located?
11. What are the horse latitudes, and where are they located?
12. What are the trade winds? Cause?
13. What are the prevailing westerlies, and where are they located?
14. Explain the general circulation.
15. What is the polar front?
16. Describe briefly an extratropical cyclone.
17. What is an anticyclone?
18. Briefly explain the polar front theory of cyclogenesis.
19. What is a föhn wind? A chinook?
20. In landing at the bottom of a deep canyon at night, what direction would you expect to find the surface winds—up the canyon or down the canyon?
21. Given a föhn wind blowing from the Great Basin region of the United States onto the Pacific Coast. The elevation is 10,000 ft. and the air temperature is 40° F. before the air begins descent. What will be the temperature at coast stations if the air descends adiabatically?
22. Illustrate by a diagram the general pressure and wind distribution on the earth. Label all highs, lows, westerlies, etc.
23. Under what conditions are surface winds most nearly parallel to the isobars?
24. How would you advise an aviator to fly on a warm afternoon over the land so that he would avoid rough air?

25. Find the volume of 1 cubic meter of air at 1000 meters released at the surface at 20° C. and pressure of 760 mm. New pressure at 660 mm. Dew-point temperature 8° C.

26. Illustrate how föhn and katabatic winds differ.

27. A balloon of volume 500 cc is filled with helium gas to a pressure of 25 in. of mercury. Assuming the temperature is constant during ascent, what volume will the balloon occupy when the pressure changes to 12 in. of mercury?

28. If air holds 3.5 grams of water vapor in each kilogram of moist air at 1000 mb and 0° C., what is the relative humidity in % if the air is capable of holding 3.7 grams per kilogram under these conditions?

29. Define the following: (a) dyne, (b) millibar, (c) millimeter, (d) turbulence, (e) density.

30. Find the density of air at 3 atmospheres' pressure and 273° C.

V. *AIR MASSES*

A. *True* or *False*

1. Tropical Continental air is found usually over southeast U. S.
2. There are few or no gusts in an mTw air mass.
3. Clouds are cumuliform in an mPk air mass.
4. Superior air is found in the upper stratosphere and is a subsidence air mass.
5. Subsidence in an air mass will cause the lapse rate to become more unstable.
6. Cooling from below tends to make the air mass more unstable.
7. Snow squalls are hydrometeors of stable air masses.
8. An air mass is a body of air which is homogeneous in horizontal extent.
9. A cTw air mass is sometimes accompanied by fog.
10 A cPk air mass is accompanied by poor visibility.
11. The intensity of precipitation on the windward side increases with the passage of an unstable air mass over a barrier.
12. A thermodynamically warm air mass is stably stratified.
13. An air mass labeled NPp means that the air mass is non-transitional Polar Pacific.
14. An air mass is defined as a body of air which is homogeneous in vertical extent.
15. A cTw air mass has its origin in the polar regions.
16. Ocean currents influence the distribution of rainfall.
17. Precipitation is light in the Polar zones.
18. Homogeneity in an air mass is affected by vertical motions outside the "source regions."
19. If an air mass is colder than the surface over which it travels, the air will tend to become bumpy.
20. Polar Maritime air masses in summer are accompanied by convectional currents, cumulus clouds and rain as they travel inland.
21. A thermodynamically cold air mass is unstably stratified.
22. The Humboldt current in the Southern Hemisphere is a warm current circulating from the equator south along the west coast of South America.
23. Polar Continental air usually is very stable at its source region.
24. Tropical Pacific air is, in general, cooler than Tropical Atlantic air.
25. As a stable air mass approaches a mountain range its area of precipitation narrows.

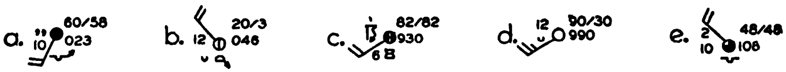
B. *Multiple Choice* and *Completion*

1. ——— lapse rates are found in winter in high latitudes.
2. An air mass is defined as a widespread body of air which approximates ———.
3. The region where the air mass attains its original characteristics is called its ———.

4. The air mass with the greatest annual variation in temperature and moisture content is (mT, cP, cT, sT).
5. Maritime tropical air has its source (north of lat. 45°, in central America, in the Gulf of Mexico, in China).
6. Sleet is a name given to (soft hail, ice needles, frozen raindrops, snow grains).
7. Drizzle is due to (cooling, warming) a stable air mass from below.
8. Showers will usually accompany (stable, unstable, neutral) air masses.
9. Heating from below tends to make an air mass (stable, unstable, neutral, unchanged).
10. Concerning diurnal variation of clouds and hydrometeors in stable air masses, there is a maximum of cloud formation at (0800-1000, noon, 2000-2200, 1400-1600).

C. *Study Questions*

1. What is an air mass? What circumstances influence the properties of air masses?
2. List by symbol all of the air masses of North America.
3. List European, Asian and Australian air masses. What are their characteristic paths?
4. List the principal properties and characteristics of Tropical Maritime air masses in summer and in winter over the land (clouds, temp., weather, stability conditions, humidity).
5. List the properties of Polar Continental air masses in summer and in winter as above.
6. Identify probable air mass associated with these stations.



7. Trace the development of an air mass originating in Northern Canada and passing southward over the Great Lakes, and finally to sea off the coast of S. Carolina.
8. What type weather might be expected at a warm front between gT air and mP air in summer?
9. Check characteristics of a "thermodynamically cold air mass" (K) in the following:

(a) Turbulent in lower levels.	(a) Little turbulence in lower levels.
(b) Stable lapse rate.	(b) Unstable lapse rate.
(c) Good visibility.	(c) Poor visibility.
(d) Cumuliform clouds.	(d) Stratoform clouds.
(e) Drizzle, mist, dew.	(e) Showers, thunderstorms, hail, sleet, snow flurries.

10. Check characteristics of "thermodynamically warm air mass" (W) in the following:

(a) Turbulent in lower layers.	(a) Smooth air (above surface friction level).
(b) Stable lapse rate.	(b) Unstable lapse rate.
(c) Good visibility.	(c) Poor visibility.
(d) Cumuliform clouds.	(d) Stratoform clouds.
(e) Showers, thunderstorms, hail, sleet, snow flurries.	(e) Drizzle, mist, dew.

11. Draw ascent curves to show the following changes in an air mass:
   a. After travel over warmer ocean.
   b. After travel over warmer continent.
   c. After travel over colder surface.

12. List all the changes that take place in a Pc air mass as it moves from its source near Hudson Bay in Canada south to the Gulf of Mexico in the winter.
13. Differentiate between homogeneous and heterogeneous.
14. If mTw air is flowing northward over a snow surface in Illinois in winter, would you expect good visibility? Why?
15. In what types of air would you expect to find "bumpiness" at high elevations?
16. What types of weather in winter would be expected in cPk, south of the Great Lakes?
17. Outline the trajectories of all North American air masses.
18. Discuss briefly the properties of the other air masses of the world.

VI. SPECIAL STORMS

A. *True* or *False*

1. A line of thunderstorms is also called a line squall when associated with a cold front.
2. Most thunderstorms over land occur at night.
3. Electric charges are built up in Cb clouds by the splitting of rain drops.
4. Dry air is a good conductor of electricity.
5. The top of a cumulonimbus cloud is negatively charged.
6. Tornadoes are found associated with tropical cyclones.
7. The latent heat of condensation furnishes the energy to maintain thunderstorms.
8. Hail falls from cirrus-nothus.
9. The term waterspout is synonymous with tropical cyclone.
10. In the Northern Hemisphere hurricanes characteristically recurve to the northeast.

B. *Multiple Choice* and *Completion*

1. The base of a convective cloud is mainly (negatively, positively) charged, while the top is (negatively, positively) charged.
2. The earth beneath the cloud is (negatively, positively) charged by induction and this has a charge opposite to the usual (negative, positive) charge of the earth in fair weather.
3. Heat lightning (does, does not) differ in physical character from streak lightning.
4. Thunderstorms dangerous to objects on the earth are favored by (high, low) humidity and by (high, low) winds aloft.
5. Lightning discharges are (alternating, direct).
6. In order for the air to be electrically conductive, ——— must be present in the atmosphere.
7. The beads in bead lightning probably represent ———.
8. The usual direction of travel of tornadoes in the United States is ———.
9. Tropical cyclones occur most frequently between latitudes ——— and ———.
10. Hurricane winds blow ——— in the Southern Hemisphere.
11. The ideal conditions for thunderstorms are found in air masses with ——— humidity and temperature.
12. The most characteristic type of air mass for wet thunderstorms is ———.
13. The top of a Cb cloud is ——— charged.
14. ——— (give stability type) air when lifted over a frontal surface may cause thunderstorms.
15. The time of maximum thunderstorm occurrence over the land is ———.
16. Over the sea this time (not season) is ———.
17. The season of maximum thunderstorm occurrence over the sea is ———.
18. Thunderstorms usually travel with the ———.

19. Air mass thunderstorms occurring close together tend to ——— each other.
20. In spring and early summer instability showers within Pc air overrunning warm surfaces may develop into ———.
21. Frontal thunderstorms need not necessarily occur at the time of ———.
22. To be classified as a thunderstorm, a storm must have ———.
23. For thunderstorms to occur the air should be conditionally unstable to at least ——— miles' altitude.
24. Thunderstorms usually approach from the ——— or ———.
25. The wind gust immediately preceding a thunderstorm is caused by ———.
26. Air mass thunderstorms are most characteristically found in ——— and shallow depressions.
27. The large water drops in a thunderstorm are ——— charged.
28. Thunder is caused by ———.
29. When Cb clouds develop high enough to intercept the ——— isotherm thunderstorms may be expected.

C. *Study Questions*

1. What causes thunder to rumble?
2. How are hailstones formed?
3. By means of a diagram, illustrate how an excessively steep lapse rate may be formed as a result of very heavy rain.
4. List the factors in a thunderstorm which might affect aircraft operation.
5. List five differences between tropical and extratropical cyclones.
6. Plot the following R.A.O.B. on the pseudo-adiabatic diagram and determine the critical temperature to which the surface air must be raised during the day to produce convective or thermal thunderstorms.

Elevation (MSL)	Pressure (mb)	Temperature (°C.)	Mixing Ratio (g/kg)
300 (Sfc)	990	16	9.0
600	950	18	9.0
1600	850	10	7.2
2400	770	5	5.5
3700	650	−4	3.5
5700	500	−14	1.9
7000	420	−17	.9

(a) Using the dry-adiabatic lapse rate of 1° C. per 100 meters, find the base of the cumulus clouds which will begin to form when the surface temperature reaches t_c.

(b) At what pressure will the 0° C. isotherm be found in the clouds?

7. A radiosonde observation made at San Antonio, Texas, was reported as follows:

(a) 25306 98732 90704 70330 30308 90280 45248 70217
10158 00147 60103 05053 40516 70564 50521 00602
10171 18631 36880 50060 72315 94036 14026 31012

Above is decoded for surface point as follows: 253 = Identifying number for San Antonio. 06 = 0600 Greenwich Civil Time. 987 = 987 mb pressure. 32 = 32° C. temperature. 90 = 90% relative humidity. 7 = Groups from beginning of message which is at 5000-ft. altitude. 0 = 10 groups from beginning of message which is at 10,000-ft. altitude. 4 = 14 groups from beginning of message which is at 20,000-ft. altitude.

Other points above surface are encoded as follows: 70 = 970 mb. (A point is arbitrary for every 100-mb change pressure.) 33 = 33° C. (Temperatures below zero are encoded by adding 50, thus −12° C. is encoded as 62 in the radiosonde code.) 0 = 100% relative humidity.

Relative humidity scale for points above surface is encoded thus: 1 = 0—19%; 2 = 20—29%; 3 = 30—39%; 4 = 40—49%; 5 = 50—59%; 6 = 60—69%; 7 = 70—79%; 8 = 80—89%; 9 = 90—94%; 0 = 95—100%.

10171 = Identifying group introducing mixing ratio groups.
18631 = Decoded: 1 = 1st and 2nd group mixing ratios follow. 86 = 28.6%. (At 32° C. and 987 mb, 100% RH = 31.8 g/kg; hence, 2 can be omitted from 28.6. Since RH = 90%, 90% × 31.8 = 28.6, encoded 86 following 1.) 31 = 33.1 since 34.1 = 100%, $\frac{33.1}{34.1} = 97\%$. 0 = 95—100%.

(b) 35304 97311 81581 12079 50108 27153 65125 08111 42052
60543 84646 00748 10171 17565 37435 56411 71214 91811

Plot the above soundings on the pseudo-adiabatic chart and answer the following questions for each.

(1) Find the LCL, CCL and MCL. What is the temperature necessary for convection?

(2) What is the dew-point temperature for each point?

(3) If the orographic lifting is available, at what altitude will the first clouds appear?

(4) Find the (a) potential (b) equivalent (c) equivalent potential (d) wet-bulb and wet-bulb potential temperature for various points.

(5) Are clouds present at the time of the soundings? Will convective clouds appear tomorrow?

VII. FOGS AND ICING CONDITIONS

A. *True* or *False*

1. Ground fog is due to adiabatic cooling.
2. Sea fog is usually an evaporation type.
3. When the vapor pressure of the overlying air, when saturated, is less than the vapor pressure of the water over which it lies, steam fog will form.
4. Mountain fog consists of clouds in contact with the higher elevation.
5. Inversions, in high inversion fog, start from the ground.
6. When the temperature and dew point coincide, fog will usually be formed.
7. Land- and sea-breeze fog is the result of non-adiabatic cooling.
8. Post-occluded front fog is an evaporation type.
9. Isobaric fog is a common type.
10. Convergence at fronts usually forms fog
11. Ground fogs are associated with surface inversions.
12. Monsoon fog will only occur where there are cold currents along the coast.
13. It is difficult to remove ice from lighter-than-air aircraft.
14. Clear ice is tenacious and adds weight
15. The icing zone can be cleared in most cases by flying through a 2000-feet vertical zone
16. There is no de-icing equipment for propellers.
17. High humidity is necessary to cause carburetor icing.
18. Ice may be formed when flying through visible moisture above the freezing temperature.
19. Clear ice may be accumulated when flying through clouds caused by orographic lifting.
20. Freezing rain zones are the least dangerous for icing.

B. *Multiple Choice* and *Completion*

1. Ice which is granular, opaque and porous is known as (rime ice, frost, clear ice).
2. Relative to clear ice, rime ice is (heavy, light, the same density).
3. Transparent layers of ice deposited by supercooled rain or drizzle may be known as (hard rime, soft rime, hoar frost, glazed frost).
4. The most severe icing will be encountered in (cirrus, cirrocumulus, altostratus, cumuliform, stratiform clouds).
5. Ice fog is (increased, dissipated, not affected) by snow-covered ground.
6. Fog formed by radiational cooling will form first (on high ground, on the level ground, in low places).

7. High-inversion fog will form more rapidly when the layers above the inversion are (very moist, medium moist, very dry).
8. Turbulence will tend to (accelerate, not affect, prevent) the formation of fog.
9. The widest and deepest belts of icing occur near (warm fronts, cold fronts, occluded fronts).
10. ——— may be encountered in clouds with strong turbulence.
11. Propellor icing may ——— the engine.
12. Carburetor icing is indicated when the engine begins to burn too ——— a mixture.
13. Icing of ——— tubes to aircraft instruments may cause severe flight miscalculations.
14. ——— should be cleared from the ship before take-off.
15. Ice may be removed by flying ——— over warm ocean currents.

C. *Study Questions*

1. Will icing be more severe in cumuliform clouds or in stratiform clouds? Why?
2. Why is it important for a pilot to know the temperature and dew point at the surface of the earth? Explain fully.
3. In a freezing rain situation, should you fly higher or lower to get out of the icing conditions. Why?
4 Explain the cause of the formation of evaporation type fogs.
5. Outline the time of year and place of occurrence of the most characteristic fogs of North America and adjacent oceans.
6. Station A is located in an industrial district, and station B is in the open country. The hourly temperature and dew-point readings are given up to 2300 time. At which station can fog be expected to form first? Why?

Time	Temperature °F.	Dew Point °F.	Station "A" Visibility miles	Station "B" Visibility miles
1900	60	55	3	30
2000	58	54	3	30
2100	56	54	2	30
2200	55	54	2	30
2300	54	53	1	30

7. Outline the precautions to be observed by pilots regarding icing conditions.
8. List and explain all of the conditions conducive to icing conditions.
9. List and explain all of the fog-producing processes.
10. How can fog be dissipated?

VIII. MAP ANALYSIS AND FORECASTING

A. *True* or *False*

1. Isobars represent the distribution of atmospheric pressure in the sea-level plain.
2. The isobars on the completed charts should be in logical sequence to those on all preceding charts.
3. Isobars at sea do not follow the gradient wind as closely as do those on land.
4. Cyclonic waves will never form on the lee side of a range after the passage of a cold front.
5. When the pressure profile of a cyclonic center is slightly curved, the speed of the center may vary within wide limits.

6. Very oblong centers generally move along the shortest symmetry axis or very close to it.
7. Rain and snow are hydrometeors of a warm front type of precipitation.
8. A cyclonic center moves toward the area of under normal winds.
9. Circular anticyclonic centers move in the direction of the isallobaric gradient.
10. Troughs and wedges whose pressure profiles have great curvature will move slowly.
11. A warm front is a zone of discontinuity where cold air is replacing warm air.
12. An unstable warm wave on a cold front will start to occlude.
13. When a cold front catches up to the warm front, an occluded front will be formed.
14. A high-pressure area is generally associated with unsettled or stormy weather.
15. Isobars are drawn perpendicular to the surface wind direction.
16. In general, cumulonimbus clouds are associated with a warm front.
17. The boundary between two dissimilar air masses is called a front, and it is here that most rainfall occurs.
18. High cirrus clouds frequently signal the approach of a warm front.
19. The speed of a trough or wedge is directly proportional to the curvature of the pressure profile.
20. The greater the speed of a cyclone, the less accurately can the time of arrival be forecast.
21. Convergence is an important factor in frontogenesis.
22. Troughs move in the direction of the isallobaric ascendant.
23. In summer, a warm front has a tendency to accentuate when passing from sea to land.
24. The center of an anticyclone moves in the direction in which the temperature is falling the fastest
25. Errors are made intentionally in reporting pressures so that a reason may be found for drawing smooth isobars.
26. The center of a depression which is not occluded will move in a direction perpendicular to the warm-sector isobars.
27. Forecasting on the basis of observations at a single station or by statistical methods is less successful than forecasting from synoptic charts.
28. Cold fronts tend to dissipate when they are accelerated.
29. A col is defined as the intersection of two trough lines.
30. Airway weather reports are sent in over the teletype every 4 hours.
31. A depression will move toward an isallobaric "high."
32. Convergence is the most important factor in causing frontolysis.
33. The occlusion process is slowed down by a mountain range during the approach and passage of a warm front followed by a cold front.
34. The character of a front cannot change from "cold" to "warm" or vice versa.
35. Each successive depression of the same family follows a track which is nearer the equator than that of its predecessor.

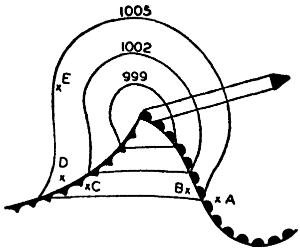
B. *Multiple Choice* or *Completion*

1. If the isobars are close together for equal increments of pressure, this is an indication of (high wind velocity, low wind velocities, a dead calm).
2. Isobars on a map represent points along which (density, pressure tendency, pressure, specific volume) is constant.
3. Every isobar must form a closed (spiral, curve, intersection, helix).
4. With the approach of a warm front, rain falls first from the (stratus, altostratus, cumulus, altocumulus) cloud system.
5. The precipitation accompanying a warm front is (the showery type, always hail, a steady rain, snow pellets).
6. The air which follows a cold front is in general (smooth, warm, bumpy, moist).

7. After the passage of a warm-type occluded front, the temperature will be (greater than, less than, the same as) before.
8. After the passage of a cold front, the visibility becomes (worse, better, remains the same).
9. During the cold-front passage, the wind will shift from (NW to NE, SW to NE, S to NE, S to NW).
10. The specific humidity (increases, decreases, remains constant) after the passage of a cold front.
11. The line on the ground which marks the boundary between warm and cold air is called a ———.
12. The passage of a warm front is characterized by the following type of barograph trace ———.

C. *Study Questions*

1. Draw a warm-type occlusion which you would expect to find in the Northern Hemisphere. Label warm front, cold front, occluded front, warm sector, and upper cold front. What type of weather would you expect in the warm sector? Also draw a cross section of the above occlusion and show what kind of an ascent curve you would get if a sounding was taken through the occluded front at the ground.
2. Show by means of a series of diagrams, the formation of an extra-tropical cyclone. Label all parts.
3. List several types of upper-air maps and tell how they are used. For what is an atmospheric cross section used?
4. Make a drawing to illustrate·
   a. Cold front structure and characteristics.
   b. Warm front structure and characteristics.
   c. Two types of occlusions.
   d. Basic premise of air mass analysis.
5. Draw a series of diagrams showing the formation of an unstable wave and the process of occlusion in the Southern Hemisphere. Label all parts.
6. Name the cloud types you would see when flying toward a warm front from the cold air side.
7 What is the difference in cloud conditions in the cold air near a slowly moving cold front, and near a rapidly moving cold front
8. Will the wind be stronger in a low or a high, both with isobars 100 miles apart and having a radius of curvature of 1000 miles? Why?
9. How are lows classified? How is precipitation related to the velocity of travel of a low?



10. The above figure represents a cyclonic system moving in the direction of the arrow. Give all the elements of the weather by filling in the table below:

Point	Pressure Tendency	Tempera-ture	Relative Humidity	Clouds	Precipi-tation	Visi-bility	Wind
A							
B							
C							
D							
E							

Where would the barometric tendency be lowest?
If the pressure at the center falls to 996 mb, will the wave occlude?

Centigrade to Fahrenheit Temperature

Centigrade	0	1	2	3	4	5	6	7	8	9
	F.	F.	F.	F.	F	F.	F.	F.	F.	F.
−50	− 58.0	−59.8	−61.6	− 63.4	−65.2	−67.0	−68.8	−70.6	−72.4	−74.2
−40	− 40.0	41.8	43.6	45.4	47.2	49.0	50.8	52.6	54.4	56.2
−30	− 22.0	23.8	25.6	27.4	29.2	31.0	32.8	34.6	36.4	38.2
−20	− 4.0	− 5.8	− 7.6	− 9.4	−11.2	−13.0	−14.8	−16.6	−18.4	−20.2
−10	+ 14.0	+12.2	+10.4	+ 8.6	+ 6.8	+ 5.0	+ 3.2	+ 1.4	− 0.4	− 2.2
− 0	+ 32.0	+30.2	+28.4	+26.6	+24.8	+23.0	+21.2	+19.4	+17.6	+15.8
+ 0	+ 32.0	+33.8	+35.6	+37.4	+39.2	+41.0	+42.8	+44.6	+46.4	+48.2
+10	+ 50.0	51.8	53.6	55.4	57.2	59.0	60.8	62.6	64.4	66.2
+20	+ 68.	69.8	71.6	73.4	75.2	77.0	78.8	80.6	82.4	84.2
+30	+ 86.0	87.8	89.6	91.4	93.2	95.0	96.8	98.6	100.4	102.2
+40	+104.0	105.8	107.6	109.4	111.2	113.0	114.8	116.6	118.4	120.2
+50	+122.0	123.8	125.6	127.4	129.2	131.0	132.8	134.6	136.4	138.2

Fahrenheit to Centigrade Temperature

Fahrenheit	0	1	2	3	4	5	6	7	8	9
	C.	C.	C.	C.	C.	C.	C.	C.	C.	C.
− 70°	−56.7	−57.2	−57.8	−58.3	−58.9	−59.4	−60.0	−60.6	−61.1	−61.7
− 60	−51.1	51.7	52.2	52.8	53.3	53.9	54.4	55.0	55.6	56.1
− 50	−45.6	46.1	46.7	47.2	47.8	48.3	48.9	49.4	50.0	50.6
− 40	−40.0	40.6	41.1	41.7	42.2	42.8	43.3	43.9	44.4	45.0
− 30	−34.4	35.0	35.6	36.1	36.7	37.2	37.8	38.3	38.9	39.4
− 20	−28.9	29.4	30.0	30.6	31.1	31.7	32.2	32.8	33.3	33.9
− 10	−23.3	23.9	24.4	25.0	25.6	26.1	26.7	27.2	27.8	28.3
− 0	−17.8	18.3	18.9	19.4	20.0	20.6	21.1	21.7	22.2	22.8
+ 0	−17.8	−17.2	−16.7	−16.1	−15.6	−15.0	−14.4	−13.9	−13.3	−12.8
+ 10	−12.2	11.7	11.1	10.6	10.0	9.4	8.9	8.3	7.8	7.2
+ 20	− 6.7	6.1	5.6	5.0	4.4	3.9	3.3	2.8	2.2	1.7
+ 30	− 1.1	− 0.6	0.0	+ 0.6	+ 1.1	+ 1.7	+ 2.2	+ 2.8	+ 3.3	+ 3.9
+ 40	+ 4.4	+ 5.0	+ 5.6	+ 6.1	+ 6.7	+ 7.2	+ 7.8	+ 8.3	+ 8.9	+ 9.4
+ 50	+10.0	10.6	11.1	11.7	12.2	12.8	13.3	13.9	14.4	15.0
+ 60	+15.6	16.1	16.7	17.2	17.8	18.3	18.9	19.4	20.0	20.6
+ 70	21.1	21.7	22.2	22.8	23.3	23.9	24.4	25.0	25.6	26.1
+ 80	26.7	27.2	27.8	28.3	28.9	29.4	30.0	30.6	31.1	31.7
+ 90	32.2	32.8	33.3	33.9	34.4	35.0	35.6	36.1	36.7	37.2
+100	37.8	38.3	38.9	39.4	40.0	40.6	41.1	41.7	42.2	42.8
+110	43.3	43.9	44.4	45.0	45.6	46.1	46.7	47.2	47.8	48.3
+120	48.9	49.4	50.0	50.6	51.1	51.7	52.2	52.8	53.3	53.9

Tables from George F. Taylor's "Aeronautical Meteorology"

Miscellaneous Constants

Specific heat of dry air at constant pressure (c_p)	= 0.2396 gram-calories per gram
Specific heat of dry air at constant volume (c_v)	= 0.1707 gram-calories per gram
Ratio of specific heats, γ (c_p/c_v)	= 1.403
Latent heat of fusion of ice	= 79.7 gram-calories per gram

Latent Heat of Vaporization of Water (L), in Gram-Calories per Gram

° C.	0	5	10	15	20	25	30
L	594.9	592.4	590.0	587.5	585.0	582.4	579.8
° C.	40	50	60	70	80	90	100
L	574.5	569.0	563.4	557.6	551.6	545.5	539.1

Beaufort Scale of Wind Velocities

Beaufort Number	Description of the Wind	Velocity	
		Statute Miles per Hour	Meters per Second
0	Calm	Less than 1	Less than 0.4
1	Light air	1 to 3	0.4 to 1.5
2	Light breeze	4 to 7	1.6 to 3.3
3	Gentle breeze	8 to 12	3.4 to 5.4
4	Moderate breeze	13 to 18	5.5 to 7.9
5	Fresh breeze	19 to 24	8.0 to 10.7
6	Strong breeze	25 to 31	10.8 to 13.8
7	Moderate gale	32 to 38	13.9 to 17.1
8	Fresh gale	39 to 46	17.2 to 20.7
9	Strong gale	47 to 54	20.8 to 24.4
10	Whole gale	55 to 63	24.5 to 28.4
11	Storm	64 to 75	28.5 to 33.5
12	Hurricane	Above 75	Above 33.5

The Standard Atmosphere

	Metric	English
Standard temperature	15° C.	59° F.
Standard temperature absolute	288° A.	
Standard pressure	760 mm. of Hg.	29.92117 in. of Hg.
Standard pressure	10332.276 kg/m²	2116.229 lb/ft²
Standard gravity	9.80665 m/sec²	32.1740 ft/sec²
Standard specific weight	1.2255 kg/m³	0.07651 lb/ft³
Standard density	0.124966 kg/m/sec	0.002378 lb/ft/sec
Standard temperature gradient	0.0065° C./m	0.00356617° F./ft
Standard isothermal temperature	−55° C.	−67° F.
Standard gas constant for air	29.2708	53.33089

Tables from George F. Taylor's "Aeronautical Meteorology"

Calculation of the Potential Temperature (θ)

Multiply the *absolute temperature* by the factor in the table below which corresponds to the existing pressure, to obtain the *Potential Temperature* (θ)

p in Millibars	0	10	20	30	40	50	60	70	80	90
0	....	3.767	3.085	2.745	2.528	2.370	2.252	2.151	2.070	2.001
100	1.943	1.888	1.842	1.800	1.762	1.726	1.695	1.666	1.639	1.613
200	1.590	1.568	1.547	1.527	1.501	1.491	1.474	1.458	1.445	1.428
300	1.414	1.401	1.388	1.376	1.365	1.353	1.342	1.332	1.321	1.312
400	1.302	1.293	1.285	1.276	1.267	1.259	1.251	1.244	1.236	1.228
500	1.221	1.214	1.207	1.200	1.194	1.188	1.182	1.176	1.170	1.164
600	1.159	1.153	1.148	1.142	1.137	1.132	1.127	1.122	1.118	1.113
700	1.108	1.104	1.099	1.095	1.091	1.086	1.082	1.078	1.074	1.070
800	1.066	1.062	1.059	1.055	1.051	1.048	1.044	1.041	1.037	1.034
900	1.031	1.028	1.024	1.021	1.018	1.015	1.012	1.009	1.006	1.003
1000	1.000	0.997	0.994	0.991	0.988	0.985	0.982	0.979	0.976	0.973

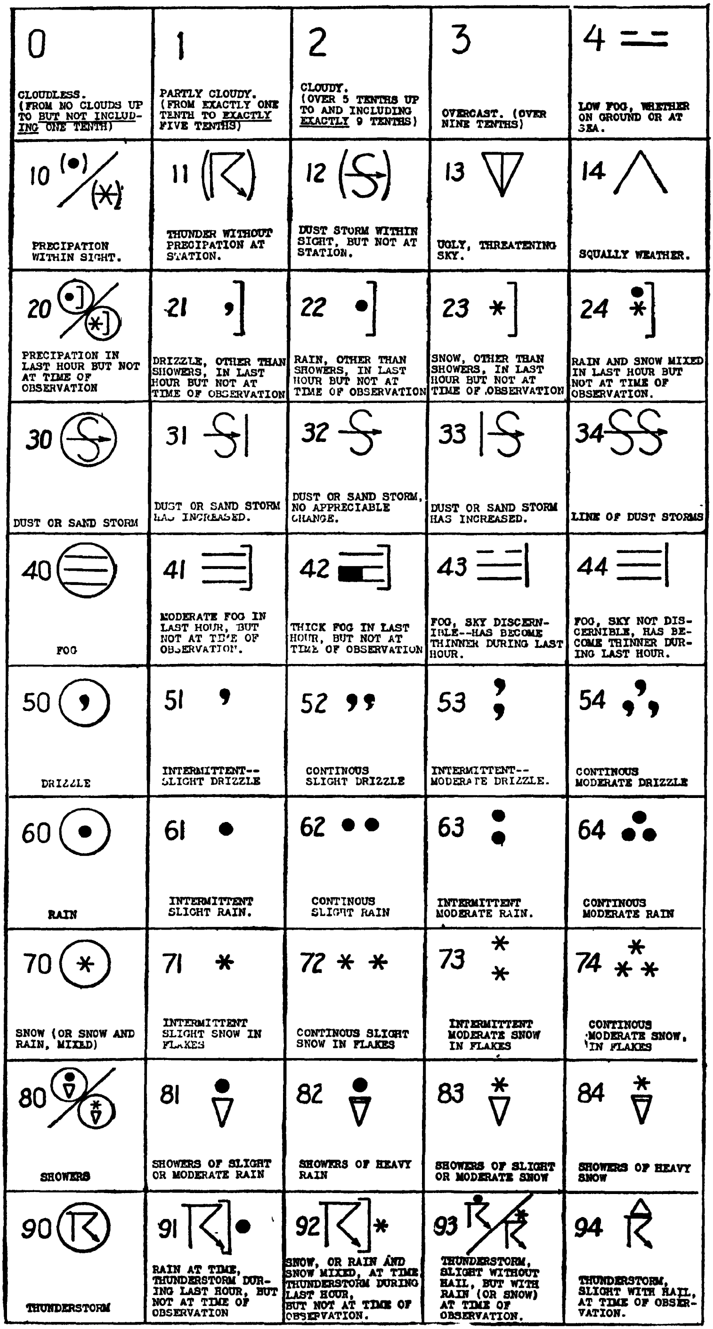
Table for $\left(\frac{p_o}{p}\right)^{.288}$ (where p_o = 1000 mb)

Calculation of the Equivalent Potential Temperature (θ_e)

Add the quantities below to the Partial Potential Temperature (θ_d) to obtain the Equivalent Potential Temperature (θ_e)

W \ θ_d	250	260	270	280	290	300	310	320	330	340	350
0.0	0	0	0	0	0	0	0	0	0	0	0
1.0	2	3	3	3	3	3	3	3	4	4	4
2.0	......	5	5	6	6	6	6	7	7	7	7
3.0	......	.....	8	8	8	9	9	9	10	10	11
4.0	......	......	10	10	11	12	12	12	13	13	14
5.0	......	......	12	13	14	14	15	15	16	17	17
6.0	......	......	...	15	16	17	18	18	19	20	21
7.0	......	......	...	18	19	19	20	21	22	23	24
8.0	......	......	...	20	21	22	23	24	25	26	27
9.0	......	......	.....	23	24	25	26	27	28	29	30
10.0	......	......	.....	25	26	27	29	30	31	32	33
11.0	......	......	.....	.....	29	30	31	33	34	35	36
12.0	......	......	.....	.....	31	33	34	35	37	38	39
13.0	......	......	.....	....	34	35	37	38	40	42	43
14.0	......	......	.....	.....	37	38	39	41	43	45	47
15.0	.....	......	.....	....	39	40	42	44	46	48	50
16.0	......	......	.....	...	41	43	45	47	49	51	53
17.0	......	......	.....	.....	44	46	48	50	52	54	56
18.0	......	......	.....	.....	46	48	50	53	55	57	60
19.0	......	......	.....	.....	49	51	53	56	58	60	63
20.0	......	......	.....	.....	51	53	56	58	61	63	66

Tables from George F. Taylor's "Aeronautical Meteorology"



From Hamburg and Tweney's "The American Student Flyer"

5 HAZE (VISIBILITY PLUS 1000m.,1100 yds.)	6 DUST DEVILS SEEN	7 DISTANT LIGHTNING	8 LIGHT FOG, (VISIBILITY 1000 TO 2000m., 1100 TO 2200 yds.)	9 FOG AT DISTANCE, NOT AT STATION.
15 HEAVY SQUALLS--IN LAST 3 HOURS	16 WATERSPOUTS SEEN--IN LAST 3 HOURS.	17 VISIBILITY REDUCED BY SMOKE.	18 DUST STORM, VISIBILITY PLUS 1100 yds.	19 SIGNS OF TROPICAL STORM (HURRICANE)
25 RAIN SHOWERS IN LAST HOUR BUT NOT AT TIME OF OBSERVATION.	26 SNOW SHOWERS IN LAST HOUR BUT NOT AT TIME OF OBSERVATION.	27 HAIL OR RAIN AND HAIL SHOWERS IN LAST HOUR BUT NOT AT TIME OF OBSERVATION	28 SLIGHT THUNDER-STORM IN LAST HOUR BUT NOT AT TIME OF OBSERVATION	29 HEAVY THUNDER-STORM IN LAST HOUR BUT NOT AT TIME OF OBSERVATION.
35 STORM OF DRIFTING SNOW.	36 SLIGHT STORM OF DRIFTING SNOW--GENERALLY LOW.	37 HEAVY STORM OF DRIFTING SNOW--GENERALLY LOW.	38 SLIGHT STORM OF DRIFTING SNOW--GENERALLY HIGH	39 HEAVY STORM OF DRIFTING SNOW GENERALLY HIGH
45 FOG, SKY DISCERNIBLE, NO APPRECIABLE CHANGE DURING LAST HOUR.	46 FOG, SKY NOT DISCERNIBLE, NO APPRECIABLE CHANGE DURING LAST HOUR.	47 FOG, SKY DISCERNIBLE--HAS BECOME THICKER DURING LAST HOUR.	48 FOG, SKY NOT DISCERNIBLE--HAS BECOME THICKER DURING LAST HOUR.	49 FOG IN PATCHES.
55 INTERMITTENT--THICK DRIZZLE.	56 CONTINOUS THICK DRIZZLE	57 DRIZZLE AND FOG	58 SLIGHT OR MODERATE DRIZZLE AND RAIN	59 THICK DRIZZLE AND RAIN.
65 INTERMITTENT HEAVY RAIN	66 CONTINOUS HEAVY RAIN	67 RAIN AND FOG	68 SLIGHT OR MODERATE RAIN OR SNOW, MIXED.	69 HEAVY RAIN AND SNOW, MIXED
75 INTERMITTENT HEAVY SNOW IN FLAKES	76 CONTINOUS HEAVY SNOW IN FLAKES	77 SNOW AND FOG	78 GRAINS OF SNOW (FROZEN DRIZZLE)	79 ICE CRYSTALS; OR FROZEN RAINDROPS (SLEET).
85 SHOWERS OF SLIGHT OR MODERATE RAIN AND SNOW.	86 SHOWERS OF HEAVY RAIN AND SNOW	87 SHOWERS OF SNOW PELLETS (SOFT HAIL)	88 SHOWERS OF SLIGHT OR MODERATE HAIL, OR RAIN AND HAIL.	89 SHOWERS OF HEAVY HAIL, OR RAIN AND HAIL.
95 THUNDERSTORM MODERATE WITHOUT HAIL, BUT WITH RAIN (OR SNOW) AT TIME OF OBSERVATION.	96 THUNDERSTORM MODERATE WITH HAIL AT TIME OF OBSERVATION.	97 THUNDERSTORM HEAVY WITHOUT HAIL, BUT WITH RAIN (OR SNOW) AT TIME OF OBSERVATION.	98 THUNDERSTORM COMBINED WITH DUST STORM AT TIME OF OBSERVATION.	99 THUNDERSTORM HEAVY WITH HAIL AT TIME OF OBSERVATION.

From Hamburg and Tweney's "The American Student Flyer"

SYMBOLS REPRESENTING WEATHER DURING SIX HOURS PRECEDING OBSERVATION

W	N	C_L	C_M	C_H	a
	0 ABSOLUTELY NO CLOUDS IN SKY	0 NO LOWER CLOUDS	0 NO MIDDLE CLOUDS	0 NO HIGH CLOUDS	0 RISING, THEN FALLING
	1 LESS THAN ONE TENTH	1 CUMULUS OF FINE WEATHER	1 TYPICAL ALTOSTRATUS, THIN	1 CIRRUS, DELICATE, NOT INCREASING, SCATTERED AND ISOLATED MASSES	1 RISING, THEN STEADY, OR RISING, THEN RISING MORE SLOWLY
	2 ONE TENTH	2 CUMULUS HEAVY AND SWELLING, WITHOUT ANVIL TOP	2 TYPICAL ALTOSTRATUS, THICK (OR NIMBOSTRATUS)	2 CIRRUS, DELICATE NOT INCREASING, ABUNDANT BUT NOT FORMING A CONTINOUS LAYER	2 UNSTEADY.
	3 TWO OR THREE TENTHS	3 CUMULONIMBUS	3 ALTOCUMULUS, OR HIGH STRATOCUMULUS, SHEET AT ONE LEVEL ONLY	3 CIRRUS OF ANVIL CLOUDS, USUALLY DENSE	3 STEADY OR RISING
	4 FOUR, FIVE, OR SIX TENTHS	4 STRATOCUMULUS FORMED BY THE FLATTENING OF CUMULUS CLOUDS	4 ALTOCUMULUS IN SMALL ISOLATED PATCHES, INDIVIDUAL CLOUDS OFTEN SHOW SIGNS OF EVAPORATION AND ARE MORE OR LESS LENTICULAR IN SHAPE	4 CIRRUS, INCREASING, GENERALLY IN THE FORM OF HOOKS ENDING IN A POINT OR IN A SMALL TUFT	4 FALLING OR STEADY, THEN RISING, OR RISING, THEN RISING MORE QUICKLY
	5 SEVEN OR EIGHT TENTHS	5 LAYER OF STRATUS OR STRATOCUMULUS	5 ALTOCUMULUS ARRANGED IN MORE OR LESS PARALLEL BANDS OR AN ORDERED LAYER ADVANCING OVER THE SKY	5 CIRRUS (OFTEN IN POLAR BANDS) OR CIRROSTRATUS ADVANCING OVER THE SKY BUT NOT MORE THAN 45 ABOVE THE HORIZON	5 FALLING, THEN RISING.
	6 NINE TENTHS	6 LOW BROKEN UP CLOUDS OF BAD WEATHER	6 ALTOCUMULUS FORMED BY A SPREADING OUT OF THE TOPS OF CUMULUS	6 CIRRUS (OFTEN IN POLAR BANDS) OR CIRROSTRATUS ADVANCING OVER THE SKY AND MORE THAN 45 ABOVE THE HORIZON	6 FALLING, THEN STEADY, OR FALLING, THEN FALLING MORE SLOWLY
	7 MORE THAN NINE TENTHS BUT WITH OPENINGS	7 CUMULUS OF FINE WEATHER AND STRATOCUMULUS	7 ALTOCUMULUS ASSOCIATED WITH ALTOSTRATUS OR ALTOSTRATUS WITH A PARTIALLY ALTOCUMULUS CHARACTER	7 VEIL OF CIRROSTRATUS COVERING THE WHOLE SKY	7 UNSTEADY.
	8 SKY COMPLETELY COVERED WITH CLOUDS	8 HEAVY OR SWELLING CUMULUS, OR CUMULONIMBUS, AND STRATOCUMULUS	8 ALTOCUMULUS CASTELLATUS, OR SCATTERED CUMULIFORM TUFTS	8 CIRROSTRATUS NOT INCREASING AND NOT COVERING THE WHOLE SKY	8 FALLING.
	9 SKY OBSCURED BY FOG, DUSTSTORM, OR OTHER PHENOMENON	9 HEAVY OR SWELLING CUMULUS (OR CUMULONIMBUS) AND LOW RAGGED CLOUDS OF BAD WEATHER	9 ALTOCUMULUS IN SEVERAL SHEETS AT DIFFERENT LEVELS, GENERALLY ASSOCIATED WITH THICK FIBROUS VEILS OF CLOUD AND A CHAOTIC APPEARANCE OF THE SKY	9 CIRROCUMULUS PREDOMINATING, ASSOCIATED WITH A SMALL QUANTITY OF CIRRUS	9 STEADY OR RISING, THEN FALLING; OR FALLING, THEN FALLING MORE QUICKLY.

From Hamburg and Tweney's "The American Student Flyer"

Temperature of the Condensation Level (° C.)

(This table may be used to calculate the lift necessary to saturate a sample of air. The difference between the air temperature and the temperature of the condensation level gives the number of hundred meters lift required to reach saturation.)

θ_e \ W	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
240	....	−42.8	34.7	29.5	26.0	23.4	21.0	19.0	17.0	15.3	14.0
242	....	−43.1	35.0	29.8	26.4	23.8	21.4	19.4	17.5	15.7	14.3
244	....	−43.4	35.3	30.4	26.8	24.2	21.8	19.8	17.9	16.1	14.7
246	....	−43.7	35.7	30.8	27.2	24.5	22.2	20.2	18.3	16.5	15.0
248	....	−44.0	36.1	31.2	27.6	24.8	22.6	20.6	18.7	16.9	15.4
250	......	−44.3	36.5	31.6	28.0	25.7	23.0	21.0	19.0	17.3	15.8
252	....	−44.6	36.9	32.0	28.4	25.6	23.4	21.3	19.4	17.7	16.2
254	....	−44.9	37.0	32.4	28.7	25.9	23.7	21.7	19.8	18.1	16.6
256	....	−45.2	37.4	32.7	29.0	26.3	24.0	22.0	20.2	18.5	17.0
258	......	−45.5	37.7	33.0	29.4	26.6	24.3	22.3	20.5	18.8	17.4
260	....	−45.8	38.0	33.4	29.8	26.9	24.7	22.6	20.9	19.1	17.8
262	....	−46.1	38.3	33.7	30.1	27.2	25.0	23.0	21.2	19.5	18.2
264	....	−46.4	38.6	34.0	30.4	27.6	25.4	23.4	21.6	19.9	18.5
266	....	−46.8	38.9	34.3	30.7	27.9	25.7	23.7	22.0	20.3	18.8
268	....	−47.1	39.2	34.6	31.0	28.2	26.0	24.0	22.3	20.7	19.2
270	....	−47.4	39.5	34.9	31.3	28.5	26.3	24.4	22.6	21.0	19.6
272	......	−47.7	39.8	35.1	31.6	28.8	26.6	24.7	23.0	21.4	20.0
274	......	−48.0	40.1	35.3	31.9	29.1	26.9	25.0	23.3	21.8	20.3
276	.....	−48.3	40.4	35.6	32.2	29.4	27.2	25.3	23.7	22.2	20.7
278	....	−48.6	40.7	35.9	32.5	29.7	27.5	25.6	24.0	22.5	21.0
280	....	−49.0	41.0	36.1	32.8	30.0	27.8	25.9	24.3	22.8	21.3
282	......	−49.3	41.2	36.4	33.1	30.3	28.1	26.2	24.6	23.1	21.7
284	....	−49.6	41.5	36.7	33.4	30.6	28.4	26.5	24.9	23.4	22.1
286	....	−49.9	41.7	37.0	33.7	30.9	28.7	26.8	25.2	23.7	22.4
288	....	−50.2	42.0	37.2	34.0	31.2	29.0	27.1	25.5	24.0	22.7
290	....	−50.5	42.2	37.5	34.3	31.5	29.3	27.4	25.8	24.2	23.0
292	......	−50.8	42.5	37.8	34.6	31.8	29.6	27.7	26.1	24.5	23.3
294	....	−51.2	42.7	38.1	34.9	32.1	29.9	28.0	26.4	24.8	23.6
296	....	−51.5	43.0	38.4	35.2	32.4	30.2	28.3	26.7	25.0	23.9
298	....	−51.8	43.2	38.7	35.5	32.7	30.4	28.6	27.0	25.3	24.2
300	....	−52.1	43.5	39.0	35.7	33.0	30.7	28.9	27.3	25.6	24.5
302	....	−52.4	43.7	39.3	36.0	33.3	31.0	29.1	27.6	25.9	24.8
304	....	−52.7	44.0	39.6	36.2	33.6	31.3	29.4	27.9	26.2	25.0
306	....	−53.0	44.2	39.9	36.5	33.9	31.6	29.7	28.1	26.5	25.2
308	....	−53.3	44.5	40.2	36.7	34.2	31.9	30.0	28.3	26.8	25.5
310	....	−53.6	44.7	40.4	37.0	34.5	32.2	30.2	28.6	27.1	25.8
312	....	−53.9	45.0	40.7	37.2	34.8	32.4	30.5	28.8	27.4	26.1
314	....	−54.2	45.2	40.9	37.5	35.0	32.7	30.8	29.1	27.7	26.4
316	....	−54.5	45.5	41.2	37.7	35.2	33.0	31.0	29.3	28.0	26.7
318	....	−54.9	45.7	41.5	37.9	35.5	33.3	31.3	29.5	28.2	27.0
320	....	−55.2	46.0	41.8	38.1	35.8	33.6	31.5	29.8	28.5	27.2
322	....	−55.5	46	42.0	38.4	36.0	33.8	31.8	30.0	28.8	27.5
324	....	−55.8	46.6	42.2	38.7	36.3	34.0	32.1	30.3	29.0	27.8
326	....	−56.1	46.9	42.4	39.0	36.5	34.3	32.4	30.6	29.2	28.1
328	....	−56.4	47.1	42.6	39.2	36.7	34.5	32.7	30.8	29.4	28.4
330	....	−56.7	47.4	42.8	39.5	36.9	34.8	33.0	31.1	29.7	28.6
332	....	−57.0	47.6	43.0	39.8	37.1	35.0	33.3	31.3	30.0	28.8
334	....	−57.4	47.9	43.2	40.0	37.4	35.2	33.5	31.5	30.2	29.0
336	....	−57.7	48.1	43.4	40.3	37.6	35.5	33.8	31.8	30.5	29.3
338	....	−58.0	48.4	43.6	40.5	37.8	35.7	34.0	32.1	30.7	29.6
340	....	−58.3	48.7	43.8	40.7	38.0	36.0	34.3	32.4	31.0	29.9
342	....	−58.6	49.0	44.0	41.0	38.3	36.2	34.5	32.7	31.2	30.2
344	....	−58.9	49.2	44.2	41.2	38.5	36.4	34.8	33.0	31.5	30.4
346	....	−59.2	49.5	44.4	41.5	38.8	36.6	35.0	33.2	31.7	30.7
348	....	−59.5	49.7	44.7	41.7	39.0	36.8	35.3	33.5	32.0	30.9
θ_e / W	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0

From George F. Taylor's "Aeronautical Meteorology"

TEMPERATURE OF THE CONDENSATION LEVEL (° C.)—*Continued*

θ_e \ W	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0
250	−15.8	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
252	−16.2	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
254	−16.6	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
256	−17.0	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
258	−17.4	11.7	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
260	−17.8	12.0	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
262	−18.2	12.4	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
264	−18.5	12.7	− 7.5	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
266	−18.8	13.0	− 7.9	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
268	−19.2	13.4	− 8.3	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
270	−19.6	13.7	− 8.7	− 4.7	.....	.....	.....	.....	.....	.....	.....	.....	.....
272	−20.0	14.1	− 9.0	− 5.1	− 2.1	.....	.....	.....	.....	.....	.....	.....	.....
274	−20.3	14.5	− 9.3	− 5.5	− 2.5	.....	.....	.....	.....	.....	.....	.....	.....
276	−20.7	14.9	− 9.6	− 5.9	− 2.9	− 0.1	.....	.....	.....	.....	.....	.....	.....
278	−21.0	15.3	10.0	− 6.3	− 3.3	− 0.6	+ 1.9	.....	.....	.....	.....	.....	.....
280	−21.3	15.6	10.4	− 6.7	− 3.7	− 1.0	+ 1.5	.....	.....	.....	.....	.....	.....
282	−21.7	16.0	10.8	− 7.1	− 4.1	− 1.4	+ 1.2	+ 3.4	.....	.....	.....	.....	.....
284	−22.1	16.4	11.1	− 7.5	− 4.4	− 1.8	+ 0.8	+ 3.0	+5.0	.....	.....	.....	.....
286	−22.4	16.7	11.5	− 7.9	− 4.8	− 2.1	+ 0.4	+ 2.6	+4.6	.....	.....	.....	.....
288	−22.7	17.0	11.9	− 8.3	− 5.2	− 2.5	0.0	+ 2.2	+4.2	+6.0	.....	.....	.....
290	−23.0	17.4	12.3	− 8.7	− 5.6	− 2.9	− 0.4	+ 1.8	+3.8	+5.7	+7.4	.....	.....
292	−23.3	17.7	12.7	− 9.0	− 6.0	− 3.3	− 0.8	+ 1.4	+3.4	+5.3	+7.0	+8.6	.....
294	−23.6	18.1	13.0	− 9.4	− 6.4	− 3.7	− 1.2	+ 1.0	+3.0	+4.9	+6.6	+8.2	+9.8
296	−23.9	18.4	13.4	− 9.7	− 6.8	− 4.0	− 1.6	+ 0.6	+2.6	+4.5	+6.2	+7.9	+9.4
298	−24.2	18.7	13.7	10.0	− 7.1	− 4.3	− 2.0	+ 0.2	+2.3	+4.1	+5.8	+7.5	+9.0
300	−24.5	19.0	14.0	10.4	− 7.5	− 4.7	− 2.4	− 0.2	+1.9	+3.7	+5.4	+7.1	+8.6
302	−24.8	19.3	14.4	10.8	− 7.9	− 5.1	− 2.7	− 0.6	+1.6	+3.3	+5.0	+6.7	+8.2
304	−25.0	19.6	14.7	11.1	− 8.2	− 5.5	− 3.1	− 1.0	+1.2	+2.9	+4.6	+6.3	+7.8
306	−25.2	20.0	15.0	11.5	− 8.5	− 5.9	− 3.5	− 1.4	+0.8	+2.5	+4.2	+5.9	+7.4
308	−25.5	20.3	15.4	11.9	− 8.8	− 6.3	− 3.9	− 1.8	+0.4	+2.1	+3.8	+5.5	+7.0
310	−25.8	20.6	15.7	12.2	− 9.1	− 6.7	− 4.3	− 2.1	0.0	+1.8	+3.5	+5.1	+6.6
312	−26.1	20.9	16.0	12.5	− 9.5	− 7.0	− 4.6	− 2.5	−0.4	+1.4	+3.1	+4.7	+6.3
314	−26.4	21.2	16.4	12.8	− 9.9	− 7.3	− 4.9	− 2.8	−0.8	+1.0	+2.8	+4.3	+5.9
316	−26.7	21.5	16.7	13.1	10.3	− 7.7	− 5.2	− 3.1	−1.1	+0.7	+2.4	+4.0	+5.5
318	−27.0	21.8	17.0	13.4	10.6	− 8.0	− 5.6	− 3.5	−1.5	+0.3	+2.0	+3.6	+5.1
320	−27.2	22.1	17.2	13.7	10.9	− 8.3	− 6.0	− 3.9	−1.8	0.0	+1.7	+3.2	+4.8
322	−27.5	22.4	17.5	14.0	11.1	− 8.6	− 6.3	− 4.2	−2.2	−0.3	+1.3	+2.9	+4.5
324	−27.8	22.7	17.8	14.2	11.4	− 9.0	− 6.7	− 4.5	−2.5	−0.7	+1.0	+2.6	+4.1
326	−28.1	23.0	18.1	14.5	11.8	− 9.3	− 7.0	− 4.8	−2.9	−1.0	+0.6	+2.2	+3.7
328	−28.4	23.3	18.4	14.8	12.1	− 9.6	− 7.3	− 5.1	−3.2	−1.4	+0.2	+1.8	+3.3
330	−28.6	23.6	18.7	15.1	12.4	− 9.9	− 7.6	− 5.5	−3.6	−1.8	−0.1	+1.5	+3.0
332	−28.8	23.9	18.9	15.4	12.7	10.2	− 8.0	− 5.9	−4.0	−2.2	−0.4	+1.1	+2.7
334	−29.0	24.2	19.2	15.7	13.0	10.5	− 8.3	− 6.2	−4.3	−2.5	−0.7	+0.8	+2.4
336	−29.3	24.5	19.5	16.0	13.3	10.8	− 8.6	− 6.5	−4.6	−2.8	−1.0	+0.5	+2.0
338	−29.6	24.7	19.8	16.3	13.6	11.1	− 8.9	− 6.8	−4.9	−3.1	−1.4	+0.1	+1.6
340	−29.9	24.9	20.1	16.6	13.9	11.4	− 9.2	− 7.1	−5.2	−3.5	−1.8	−0.3	+1.3
342	−30.2	25.1	20.4	16.9	14.2	11.7	− 9.5	− 7.5	−5.5	−3.8	−2.1	−0.6	+1.0
344	−30.4	25.4	20.6	17.2	14.5	12.0	− 9.8	− 7.8	−5.9	−4.1	−2.4	−0.9	+0.7
346	−30.7	25.6	20.8	17.5	14.8	12.3	10.1	− 8.1	−6.2	−4.4	−2.7	−1.2	+0.3
348	−30.9	25.9	21.0	17.8	15.0	12.6	10.4	− 8.4	−6.5	−4.7	−3.0	−1.5	0.0
350	−31.1	26.1	21.2	18.1	15.3	12.9	10.7	− 8.7	−6.8	−5.0	−3.3	−1.9	−0.4
352	.....	−26.4	21.5	18.4	15.6	13.2	11.0	− 9.0	−7.1	−5.3	−3.7	−2.2	−0.7
354	.....	.....	−21.7	18.7	15.9	13.5	11.3	− 9.3	−7.4	−5.7	−4.0	−2.5	−1.0
356	.....	.....	.....	−19.0	16.2	13.8	11.6	− 9.6	−7.8	−6.0	−4.3	−2.8	−1.4
358	.....	.....	.....	.....	−16.5	14.0	11.9	− 9.9	−8.1	−6.3	−4.6	−3.1	−1.7
360	.....	.....	.....	.....	.....	−14.3	12.1	10.2	−8.4	−6.6	−4.9	−3.4	−2.0
362	.....	.....	.....	.....	.....	.....	.....	−10.5	−8.7	−6.9	−5.2	−3.7	−2.3
364	.....	.....	.....	.....	.....	.....	.....	.....	.....	−7.2	−5.5	−4.0	−2.6
366	.....	.....	.....	.....	.....	.....	.....	.....	.....	−7.5	−5.8	−4.3	−2.9
368	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	−6.1	−4.6	−3.2
θ_e / W	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0

From George F. Taylor's "Aeronautical Meteorology"

TEMPERATURE OF THE CONDENSATION LEVEL (° C.)—*Continued*

7 5	8 0	8.5	9 0	9 5	10 0	10.5	11.0	11 5	12.0	12.5	13.0	13.5	W / θ_e
....	....	....	....	....	....	....	....	....	....	....	....	....	250
....	....	....	....	....	....	....	....	....	....	....	....	....	252
....	....	....	....	....	....	....	....	....	....	....	....	....	254
....	....	....	....	....	....	....	....	....	....	....	....	....	256
....	....	....	....	....	....	....	....	....	....	....	....	....	258
....	....	....	....	....	....	....	....	....	....	....	....	....	260
....	....	....	....	....	....	....	....	....	....	....	....	....	262
....	....	....	....	....	....	....	....	....	....	....	....	....	264
....	....	....	....	....	....	....	....	....	....	....	....	....	266
....	....	....	....	....	....	....	....	....	....	....	....	....	268
....	....	....	....	....	....	....	....	....	....	....	....	....	270
....	....	....	....	....	....	....	....	....	....	....	....	....	272
....	....	....	....	....	....	....	....	....	....	....	....	....	274
....	....	....	....	....	....	....	....	....	....	....	....	....	276
....	....	....	....	....	....	....	....	....	....	....	....	....	278
....	....	....	....	....	....	....	....	....	....	....	....	....	280
....	....	....	....	....	....	....	....	....	....	....	....	....	282
....	....	....	....	....	....	....	....	....	....	....	....	....	284
....	....	....	....	....	....	....	....	....	....	....	....	....	286
....	....	....	....	....	....	....	....	....	....	....	....	....	288
....	....	....	....	....	....	....	....	....	....	....	....	....	290
....	....	....	....	....	....	....	....	....	....	....	....	....	292
....	....	....	....	....	....	....	....	....	....	....	....	....	294
+11.0	....	....	....	....	....	....	....	....	....	....	....	....	296
+10.6	11 9	....	....	....	....	....	....	....	....	....	....	....	298
+10.2	11.5	12.9	....	....	....	....	....	....	....	....	....	....	300
+9.7	11.2	12 5	13 8	....	....	....	....	....	....	....	....	....	302
+9.3	10.8	12 1	13.4	....	....	....	....	....	....	....	....	....	304
+8 9	10.3	11.7	13.0	14 3	....	....	....	....	....	....	....	....	306
+8.5	+9.9	11.3	12.6	13 9	15.2	....	....	....	....	....	....	....	308
+8.1	+9 5	10.9	12.2	13 5	14.7	15.8	17.0	....	....	....	....	....	310
+7.7	+9.1	10.5	11.8	13.1	14.3	15.4	16.6	....	....	....	....	....	312
+7.3	+8.7	10.1	11 4	12.7	13 9	15 0	16.2	17.3	18.3	....	....	....	314
+7.0	+8.3	+9.7	11 0	12 3	13.5	14 6	15.8	16.9	17 9	19 2	....	....	316
+6.6	+7.9	+9.3	10.6	11.9	13.1	14.2	15.4	16.5	17.5	18.6	19.6	....	318
+6.2	+7.5	+9 0	10 2	11.6	12.7	13.8	15.0	16.1	17.2	18.2	19 2	20.0	320
+5.8	+7.2	+8.6	+9.8	11.2	12.4	13.4	14.6	15.7	16.8	17.8	18.8	19.7	322
+5.4	+6.8	+8.2	+9.4	10 8	12 0	13.0	14.2	15.3	16.4	17.4	18.4	19.4	324
+5.1	+6.5	+7.8	+9 0	10.4	11.6	12.7	13.8	14.9	16.0	17.0	18.0	19.0	326
+4.7	+6 1	+7.4	+8.7	10.0	11.2	12.4	13.4	14.5	15.6	16.6	17.6	18.6	328
+4.3	+5.8	+7.0	+8.4	+9.6	10.8	12.0	13.0	14.1	15.2	16.2	17.2	18.2	330
+4.0	+5.4	+6.6	+8 0	+9.2	10 4	11.6	12.6	13.7	14.8	15.8	16.8	17.8	332
+3.7	+5.0	+6.3	+7.8	+8.8	10 0	11.2	12.3	13.4	14.4	15.5	16.5	17.5	334
+3.4	+4.6	+5.9	+7.2	+8.5	+9.6	10.8	11.9	13.0	14.0	15.1	16.1	17.1	336
+3.0	+4 3	+5.6	+6.9	+8.1	+9 2	10.4	11.5	12.6	13.6	14.7	15.7	16.7	338
+2.7	+4 0	+5.3	+6 5	+7.7	+8.9	10 0	11.1	12 2	13.2	14.3	15.3	16.3	340
+2.3	+3.7	+5.0	+6.1	+7.4	+8.6	+9.6	10.7	11 8	12.9	14.0	15.0	15.9	342
+2.0	+3.4	+4.7	+5.7	+7 0	+8 2	+9.3	10.4	11.5	12.6	13.6	14.6	15.5	344
+1.7	+3 0	+4.3	+5 4	+6.7	+7.8	+9.0	10.0	11.1	12.2	13.2	14.2	15.2	346
+1.3	+2 7	+4.0	+5.1	+6.3	+7.5	+8.6	+9.6	10.7	11.8	12.8	13.8	14.8	348
+1.0	+2.3	+3.7	+4.8	+6 0	+7.2	+8.2	+9.3	10 3	11.5	12.4	13.4	14.4	350
+0.7	+2.0	+3.3	+4.5	+5.7	+6 8	+7 8	+9.0	10 0	11 1	12.0	13.0	14.0	352
+0.4	+1.6	+3.0	+4 2	+5.4	+6.5	+7 5	+8 7	+9.7	10 7	11.7	12.7	13 7	354
0.0	+1.3	+2.7	+3.8	+5.0	+6 2	+7.2	+8 3	+9.3	10.4	11.4	12.4	13 4	356
−3 3	+1 0	+2 3	+3.5	+4.7	+5 9	+6.8	+7.9	+9.0	10.0	11.0	32.0	13.0	358
−0 6	+0 8	+2.0	+3.2	+4 4	+5.6	+6 5	+7.6	+8 7	+9.7	10 7	11.6	12.7	360
−0.9	+0.5	+1.6	+2 9	+4.0	+5.2	+6.2	+7.3	+8.3	+9 4	10.4	11.3	14.2	362
−1.2	+0.1	+1.3	+2 5	+3.7	+4.9	+5 9	+7 0	+8.0	+9 0	10.0	11.0	12.0	364
−1.5	−0.3	+1.0	+2.2	+3.4	+4.6	+5.6	+6.7	+7 7	+8.7	+9.7	10.7	11.6	366
−1.8	−0.5	+0.7	+1 9	+3 0	+4.2	+5.3	+6.4	+7.4	+8.3	+9.4	10.4	11.2	368
7.5	8.0	8.5	9.0	9.5	10.10	10.5	11.0	11.5	12.0	12.5	13.0	13.5	θ_e / W

From George F. Taylor's "Aeronautical Meteorology"

TEMPERATURE OF THE CONDENSATION LEVEL (° C.)—*Continued*

θ_e \ W	14.0	14 5	15 0	15.5	16 0	16.5	17.0	17.5	18 0	18 5	19.0	19.5	20.0
322	+20 8	.....	.....	.....	.....	.....	.....	.....	...	.....	.....	.....	.....
324	+20.4	21.4	.....	.....	.....	.....	.....	.....	...	....	.....	.....	.....
326	+20.0	21.0	21.8	.....	.....	....	.....	.....	.....	.. .	....	.....	.....
328	+19.6	20.6	21.4	22.4	.....	...	. . .	.....	..	.....	.....	.....	.....
330	+19 2	20 2	21 0	22.0	23.0	.....	.....	.. ...	. .	.....	.....	.....	.....
332	+18 8	19.8	20.7	21.6	22.5	23.4	.....	.....	....	.....	.....	.....	.....
334	+18.4	19.3	20.3	21 2	22.1	23 0	23.6	.....	.....	.....	.....	.....	.....
336	+18 0	18 9	19.9	20.8	21.7	22 6	23.3	24.2	25 1	.....	.....	.....	.....
338	+17.6	18 5	19.5	20 4	21.3	22 2	23 0	23.8	24.7	.....	.....	.....	.....
340	+17 3	18.1	19.1	20.0	20 9	21.8	22.6	23 5	24 3	25 1	25 8	.....	.....
342	+16.9	17.7	18.7	19.6	20.5	21.4	22.2	23.1	23 9	24.7	25.5	26.3	.....
344	+16.5	17.3	18.3	19.2	20.1	21.0	21.8	22.7	23 6	24 3	25 1	25.9	26.6
346	+16.1	17.9	17 9	18.8	19.7	20 6	21.4	22.3	23 2	23.9	24 7	25.5	26.2
348	+15 7	16.6	17.6	18.5	19.3	20 2	21.0	21 9	22.8	23 5	24.3	25.1	25.8
350	+15 4	16.3	17.2	18.1	19.0	19.8	20.7	21.6	22.4	23 2	23.9	24.8	25.4
352	+15 0	15.9	16.8	17 7	18.6	19.5	20.3	21.2	22 0	22.8	23.6	24.4	25.0
354	+14.6	15.5	16 5	17.3	18.3	19 1	19.9	20.8	21 6	22.4	23.2	24.0	24.7
356	+14 3	15 2	16.1	17.0	17 9	18 7	19.5	20.5	21.2	22 0	22 8	23.6	24.3
358	+13 9	14.8	15.7	16.6	17.5	18.4	19.2	20.1	20.8	21.6	22.4	23.2	23.9
360	+13.6	14.5	15.4	16.2	17 1	18 0	18.8	19.7	20.4	21.2	22.1	22.8	23.5
362	+13.2	14.1	15.0	15.9	16.8	17 6	18.4	19.3	20.1	20.9	21.7	22.4	23.1
364	+12.9	13 8	14.7	15.5	16.4	17 3	18.1	18.9	19 7	20.5	21.4	22.0	22.8
366	+12 6	13.4	14.3	15.2	16.1	17 0	17.8	18.6	19.4	20.2	21.0	21.7	22.5
368	+12.2	13 0	13.9	14.8	15.7	16.7	17.4	18.3	19.0	19.8	20.7	21.4	22.1
θ_e / W	14.0	14.5	15 0	15.5	16 0	16.5	17.0	17.5	18 0	18 5	19.0	19.5	20.0

From George F. Taylor's "Aeronautical Meteorology"

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